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THE EFFECT OF SODIUM ON WATER MOVEMENT IN A DUAGH-MALMO SOIL ASSOCIATION

by

© WILLIAM R.A. HARRON

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF SOIL SCIENCE

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Fall, 1979

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled THE EFFECT OF SODIUM ON WATER MOVEMENT IN A DUAGH-MALMO SOIL ASSOCIATION submitted by WILLIAM R.A. HARRON in partial fulfilment of the requirements for the degree of Master of SCIENCE

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ABSTRACT

A study was conducted to assess the effect of the sodium levels on water movement in a Solonetzic soil association from the Black Soil Zone in East-Central Alberta. Consideration was given to other factors that control water flow in soils.

The soils were sampled from two research plots that had been treated with several chemical amendments intended to alter the sodium levels in the soil. Since the natural variability in Solonetzic soils is high, differences in the SAR levels due to treatment were not significant except for two nitrogen treatments that significantly lowered the sodium levels in the A horizon.

An equation relating SAR to ESP was developed for each of the A and B horizons in order to determine the adsorbed sodium levels from the analysis of the saturated paste extract. The B horizon in the soils complex adsorbs sodium at three times the rate for the A horizon. Differences in the adsorption of sodium between the two horizons are due to differences in soil properties that affect the exchange complex. The most important properties are the organic matter and clay contents. Unique SAR-ESP relationships should be determined for soils that vary significantly in either of these two properties.

Water flow was measured by saturated hydraulic conductivity of disturbed samples and vertical infiltration into dry samples. Both water movement measurements in the

B horizon showed no decrease in moisture movement until a critical SAR was reached. Once the critical sodium level was exceeded, the SAR strongly controlled movement until the sodium levels were so restrictive that there was no further decline with increased SAR.

The saturated hydraulic conductivity was more sensitive to the levels of sodium than was the infiltration, both in the level of SAR necessary to cause reduction in flow and the magnitude of the decrease. The hydraulic conductivity of the B horizon decreased through four orders of magnitude between an SAR of three and an SAR of fourteen.

The level of sodium that initiates a decline of hydraulic conductivity within the B horizon is significant in that it corresponds to the ratio between exchangeable calcium and sodium of ten that divides Solonetzic and Chernozemic soils. At an ESP of 15, which is used to classify sodic soils, the hydraulic conductivity of the B horizon has almost reached its minimum values.

Within the range of SAR in the A horizon of the Duagh-Malmo soil association, the level of adsorbed sodium did not affect water movement. The different response of the A horizon to the sodium level in the soil compared to the B horizon could be attributed to differences in the rate of sodium adsorption, organic matter and clay content between the two horizons.

The level of adsorbed sodium in the B horizon of The Duagh-Malmo soil association controls water movement

over a narrow range of SAR values. Other soil properties, especially the clay and organic matter contents have significant effects in altering the relationship between sodium and water movement.

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I. INTRODUCTION

Soils of the Solonetzic Order are characterized by a Bnt horizon which has a ratio of exchangeable calcium to exchangeable sodium of less than ten and morphologically has a dense columnar or prismatic structure (Canada Soil Survey Committee 1978). The undesirable physical characteristics of low permeability, high bulk density, high plasticity when wet and high breaking strength when dry, lead to inadequate aeration, poor root penetration and slow water movement. Since water movement in even some A horizons of Solonetzic soils is very slow (Cairns and van Schaik 1968), alternate waterlogging and droughtiness may occur as the result of ponding after rainfall and subsequent evaporation from the upper horizons. The physical properties and related problems of Solonetzic soils are related to the soil chemistry as it has long been established that sodium has a deleterious effect on the physical properties of soils (Joffe and Zimmerman 1944, Odynsky 1945).

The relationship between the sodium level in the soil and the rate of water movement is important in predicting how soils will respond to a particular treatment. Krogman and Milne (1968) showed that hydraulic conductivity is an important factor in the productivity of a Brown Solonetz and in their study, the hydraulic conductivity was related to the sodium level of the soil.

Although much work has been done on determining the

effect of adsorbed sodium levels on the rate of water movement in soils, it has been very difficult to quantify the relationship between these two properties and apply it to varying soils. One of the greatest difficulties in understanding the effect of soil chemistry on water movement is determining the influence of other soil properties in this relationship. In this study, the effect of the sodium status on water movement in an association of soils ranging from an Eluviated Black Chernozem to a Black Solonetz is investigated with consideration of the involvement of other chemical and physical factors.

2. LITERATURE REVIEW

2.1 Factors affecting hydraulic conductivity

The factors that influence hydraulic conductivity of a soil depend mainly on the type and amount of clay, the cations on the exchange complex, the soil solution composition and concentration and the presence of other materials such as organic matter and amorphous oxides (Rowell et al. 1969). The relationship between the factors is often complex, which makes it quite difficult to state how one individual factor controls hydraulic conductivity in a wide variety of soils.

The type of clay mineral affects hydraulic conductivity under high sodium, low salt conditions. Montmorillonite has been shown to be more susceptible to swelling and dispersion than vermiculite (Rhoades and Ingvalson 1969), kaolinite (Velasco-Molina et al. 1971; Frenkel et al. 1978) and micaeous minerals (Velasco-Molina et al. 1971), but all the clays contribute to reduced hydraulic conductivity at high levels of adsorbed sodium. An exception to this is acid kaolinite. A soil which contained acid kaolinite was not affected by leaching with distilled water at an Exchangeable Sodium Percentage (ESP) of twenty (Frenkel et al. 1978), but the addition of two percent montmorillonite to this soil reduced the hydraulic conductivity by more than two orders of magnitude. Therefore, the expanding minerals such as montmorillonite are very

important in controlling hydraulic conductivity in soils (Dane 1978). In a Solonetzic soil studied by Klages (1966), most of the fine and almost all of the very fine clays were montmorillonite. For soils of similar mineralogy, a higher clay content caused reduced hydraulic conductivity (McNeal et al. 1968) as well as increased sensitivity to high sodium levels at low solution concentrations (Frenkel et al. 1978).

Cementing and bonding agents such as organic matter and amorphous oxides in association with the clay have an effect on the swelling of clay (Rowell et al. 1969) and the resulting hydraulic conductivity of the soil. Velasco-Molina et al. (1971) stated that high iron oxide contents in a kaolinite soil stabilized aggregates even at a high ESP. A study showed that the removal of easily extractable iron oxides significantly reduced the hydraulic conductivity of soils that had high iron oxide contents (McNeal et al. 1968). On the same soils, McNeal and his associates felt that any organic matter that was removed with the iron was not as important as the oxides in stabilizing the soil aggregates. However, in soils with low amorphous oxide contents, the removal of the organic matter reduces the stability of soil aggregates (Collis-George and Smiles 1963). The organic matter binds the aggregates strongly enough to prevent deflocculation under chemical conditions that are conducive to clay swelling which would lead to hydraulic conductivity decline.

Organic matter and amorphous oxides have different exchange properties than the crystalline clays. The preference for calcium over other cations such as magnesium has been shown by organic matter (Salmon 1964) and by hydroxylalumina compounds (Hunsaker and Pratt 1971). In the upper soil horizons, where organic matter content is generally high, greater adsorption of calcium than of other cations (Poonia and Talibudeen 1977) leads to almost complete removal of sodium and magnesium and poor penetration of calcium into the sub-soil (Rible and Davis 1955). Thus, organic matter can stabilize soil aggregates by both cementation and preferential adsorption of divalent cations.

When exchangeable cations are in equilibrium with the soil solution, the amount and type of adsorbed ion has a significant effect on the hydraulic properties of the soil. When cations are strongly adsorbed to the clay, there is little tendency for repulsion and swelling between clay particles. Since the strength of adsorption depends on the size and charge of the exchangeable cations (Bower 1959), the effectiveness of cations in adsorbing to the clay should be in the order of calcium > magnesium > ammonium = potassium > sodium. This is based on the surface charge density of the hydrated ion (Table 1).

Calcium is usually the dominant cation in normal soils (Kelley 1964) and it is used as a basis for comparison with the other cations since it is adsorbed so strongly that it counteracts the effects of lesser adsorbed cations such as

TABLE 1

ADSORPTION AFFINITIES OF CATIONS

Cation	*Hydrated Radius (Å)	Surface Charge Density Valence (Å)	Relative Adsorption Affinity
Ca^{++}	4.12	9.38×10^{-3}	1.00
Mg^{++}	4.28	8.69×10^{-3}	0.926
NH_4^+	3.31	7.26×10^{-3}	0.774
K^+	3.31	7.26×10^{-3}	0.774
Na^+	3.58	6.21×10^{-3}	0.662

*(Nightingale 1958)

magnesium or sodium (Joffe and Zimmerman 1944). Calcium clays will form tactoids or packets of four to five plates where the strength of adsorption of calcium is sufficient to prevent interlayer swelling even at low solution concentration (Shainberg et al. 1971). Sodium, a large monovalent cation, is at the opposite extreme since it is not adsorbed strongly (Kirkham and Powers 1972). Platelets in a sodium clay are separated (Shainberg et al. 1971) with all the surfaces participating in concentration dependent interlayer swelling (McNeal 1970). Expansion of a sodium clay may occur at a solution concentration of less than one Normal (Waldron and Constantin 1970) and at low concentrations the swelling may proceed until the platelets are completely dispersed (Norrish 1972).

Although the beneficial effects of calcium and the deleterious effects of sodium are well recognized, there is some debate concerning the effect of other cations on soil physical properties. Most of the controversy has been in respect to the relative strengths of adsorption of magnesium compared to calcium. There is sufficient evidence to indicate that magnesium should occupy a position below that of calcium, as shown in Table 1, although many authors consider the effects of the two cations to be equal.

The type of exchange complex is important in comparing calcium and magnesium adsorption. Beckett (1965) attributed higher rates of exchange for calcium over magnesium to a greater number of specific exchange sites for

calcium than magnesium. Montmorillonite shows a slight preference for calcium (Hunsaker and Pratt 1971) but illites show little preference in the adsorption of the two cations (Salmon 1964). As stated earlier, hydroxylalumina compounds (Hunsaker and Pratt 1971) and organic matter (Salmon 1964) adsorb calcium much more strongly than magnesium. Since the relative affinities of calcium and magnesium depend on the type of exchange material (Kelley 1964), different soils will adsorb magnesium at different strengths (Salmon 1964).

Magnesium is not as effective as calcium in reducing the effects of weakly adsorbed cations such as sodium. Magnesium can enhance the dispersion of illite (Emerson and Chi 1977). A magnesium dominated illite will disperse at a level of adsorbed sodium that is half of the amount necessary to disperse a calcium dominated illite (Chi et al. 1977). Similarly, Joffe and Zimmerman (1944) and Kelley (1964) stated that a high ratio of calcium to magnesium is more effective in reducing the swelling caused by sodium adsorption than a low ratio of the two cations. Van der Merwe and Burger (1969) showed that a magnesium-sodium soil has poorer physical properties than a calcium-sodium soil of equal ionic proportions.

Although magnesium is not as beneficial to the soil as calcium, in many cases, the effects have been considered close enough to consider the cations together. McNeal et al. (1968) stated that in hydraulic conductivity experiments,

calcium and magnesium could be used interchangeably. Although the replacing of a sodium-calcium solution with a sodium-magnesium solution of equal ionic ratio and concentration caused a reduction in water movement in their experiments, the difference was within the range of accuracy expected for laboratory hydraulic conductivity measurements (McNeal et al. 1968).

Ammonium and potassium have the same surface charge density which lies between the values for calcium and sodium (Table 1). The effects of the former pair of cations on soil physical properties are similar and are intermediate with respect to calcium and sodium (Martin and Richards 1959). The deflocculation of potassium and ammonium saturated clays can only be accomplished after the soils have been physically fragmented (Rowell 1963), although a sodium soil will deflocculate as the result of spontaneous swelling of the clay particles. Once deflocculated, the dispersed ammonium tactoids are approximately two clay platelets thick which is half the thickness for dispersed calcium packets and twice the value for the single clay platelets of dispersed sodium tactoids (van Schaik and Cairns 1974).

Experiments on the flow of water through soils that have been treated with ammonium or potassium show that the effect of either of the cations is intermediate to the changes caused by calcium or sodium in the soil. van Schaik and Cairns (1969) noted that ammonium increased the hydraulic

conductivity of a sodic soil but not to the same extent that calcium, at the same concentration, had improved water flow. Gardner et al (1959) conducted unsaturated flow experiments and found that water diffusivity was equivalent in a soil with 100% exchangeable potassium to that of a soil with an ESP of 25. Diffusivity was ten times greater in a potassium saturated soil than in a sodium saturated soil.

2.2 Relationship between solution and exchangeable ions

Much work has been done in order to gain an understanding of the relationship between the adsorbed and solution phases in the soil. Most of the studies indicate that the ratio of cations in the soil solution can be used to reflect the ratio of exchangeable cations when the soil solution is in equilibrium with the cations on the exchange complex.

An equation developed by Gapon (Bolt 1955) (Appendix 7.1) states that the ratio of adsorbed cations is proportional to the ratio of cations in solution, when the concentration of the soluble cation is raised to the power of the reciprocal of the valence of the cation. Once the ratio of the cations in solution is adjusted for the valences of the cations, the Gapon equation considers that a linear relationship exists between the solution and exchangeable phases. The proportionality constant in this relationship is known as the exchange constant. The Gapon model has been criticized with respect to its adequacy to quantify ion

exchange when compared to other models such as the one developed by Eriksson (1952), (Bolt 1955; Lagerwerff and Bolt 1959; Babcock 1963).

The double layer model of Eriksson (Bolt 1955) (Appendix 7.1), like the Gapon equation, relates the ratio of cations on the exchange complex and to the adjusted ratio of cations in the solution phase but includes other factors. An important consideration is a term that is dependent on the surface charge density of the exchange material. Factors that affect surface charge density are the type and amount of clay and the amount of organic matter. Differences in these properties in soils will result in differences in surface charge density which also must be considered as a soil property. The surface charge density affects the rate of adsorption of cations and, therefore, the rate of adsorption of cations is dependent on certain soil properties.

Since the surface charge density of the soil is not considered in the Gapon equation, it must be part of the exchange constant for the linear relationship between the solution and exchangeable cations. The exchange constant is a reflection of the rate of adsorption of the cations and thus is related to intrinsic soil properties (Poonia and Talibudeen 1977). The organic matter and clay contents influence the exchange characteristics of the soil. The constant in the Gapon equation must therefore be determined for soils that differ significantly in these properties.

The double layer equation of Eriksson predicts near

linearity of the relationship between the adjusted ratio of the solution cations and the ratio of exchangeable cations at low values for the ratio of the solution cations (Babcock 1963). Because of this region of linearity in the Eriksson equation, the Gapon equation has been acknowledged as a good approximation to Eriksson's model for sodium exchange in arable soils (Lagerwerff and Bolt 1959). The limits of validity of the Gapon model have been recognized as being within a range of ESP from 1 to 70 (Bolt 1955) and a solution concentration range from 20 to 240 meq/L (Bower 1959).

The most widely used application of the Gapon equation is the relationship developed by the USDA Salinity Laboratory (Richards 1954), between SAR and Exchangeable Sodium Ratio (ESR) as follows:

$$ESR = k\ SAR,$$

where k is a proportionality constant. The ESR is the proportion of the exchange complex that is occupied by sodium and may be calculated by

$$ESR = \frac{Na\ (ads)}{CEC - Na\ (ads)}$$

where the CEC is the Cation Exchange Capacity and Na (ads) is the exchangeable sodium. The SAR is the adjusted ratio of the solution cations as measured in the saturated paste extract and is calculated by

$$SAR = \frac{[Na]}{[Ca+Mg]^{\frac{1}{2}}}\ (mmoles/L)^{\frac{1}{2}}$$

Although the SAR pools calcium and magnesium and the ESR

ignores the effect of other exchangeable ions, especially potassium (Bower 1959), the ESR is proportional with significant correlation to the SAR for many soils (Bower 1959; Paliwal and Gandhi 1976; Poonia and Talibudeen 1977).

The ESR is mathematically related to the ESP through the equation:

$$ESP = \frac{ESR\ (100)}{1 + ESR}$$

since

$$ESP = \frac{Na\ (ads)}{CEC} \times 100.$$

Therefore, the SAR is related to the ESP by

$$ESP = \frac{k\ SAR\ (100)}{1 + k\ SAR}.$$

The proportionality constant (k) between SAR and ESR corresponds to the exchange constant from the Gapon equation. As discussed previously, this exchange constant is related to soil properties and varies for different soils. Therefore, for a given soil there exists a unique function between SAR and ESP. Once the relationship between SAR and ESR can be determined for a soil, a reliable estimation of ESP can be determined from the analysis of a water extract at equilibrium conditions (Bower 1959).

2.3 Effect of sodium on water movement

Decreases in hydraulic conductivity due to sodium adsorption are the result of swelling of 2:1 expandable clays such as montmorillonite. The presence of sodium on the

exchange complex causes expansion of the clays which leads to reduced water flow by blocking of soil pores, disruption of soil aggregates and dispersion of soil particles.

Norrish (1972) recognized three stages in the swelling of montmorillonite. The first region is the result of hydration of the adsorbed cations. This could lead to a partial blocking of the soil pores (Quirk and Scofield 1955; Shainberg et al. 1971) which is reflected in an increase of intraaggregate pores space at the expense of interaggregate pore space (Dane and Klute 1977), thereby reducing the hydraulic conductivity of the soil. With sodium as the adsorbed cation, the swelling could proceed into the second region where repulsive forces develop as the result of overlap of the diffuse double layers of adjacent clay surfaces and cause separation of the clay plates (Norrish 1972). Unequal swelling causing unbalanced stresses could lead to structural failure of the aggregates (Waldron and Constantin 1968) and further reduction in hydraulic conductivity (Quirk and Scofield 1955).

Structural failure of the aggregates could allow particles to become deflocculated and disperse in the soil solution as the water content increases (Norrish 1972) and/or the soil solution concentration decreases (Quirk and Scofield 1955). Deflocculation and dispersion is the third stage of swelling. Dispersed clay particles become trapped in voids and may completely block pores (Shainberg et al. 1971; Dane 1978).

Dispersion can occur before swelling is significant enough to reduce hydraulic conductivity (Frenkel et al. 1978). This is due to the effect of the adsorption of sodium on the clay packet. The demixed ion theory of McNeal (1970) states that at low sodium concentration, the monovalent cations cannot replace the divalent cations occupying the interlayer spaces. Sodium will therefore saturate the outer surface of a clay tactoid before interlayer replacement occurs. The tactoids will develop double layer forces on the external surfaces and may disperse as a single entity. In coarse textured soils, clay packets which may even be as large as silt particles have been noted to disperse and block soil pores (McNeal et al. 1966). At high levels of exchangeable sodium, the sodium can occupy interlayer positions to permit swelling of the clay plates to allow complete dispersion. Rowell (1963) noted that at an ESP of less than 50, there was a heterogenous mixture of unswollen aggregates in a swollen gel. The proportion of unswollen aggregates increased as the ESP decreased. Sodium tends to exchange more readily on the outer surfaces of the clay aggregates than on the interlayer surfaces.

Hydraulic conductivity decline in soils with adsorbed sodium is caused by the disruptive nature that sodium has on the particle arrangement within the soil. Since the processes of swelling, aggregate failure and deflocculation are controlled by the level of exchangeable sodium, the soil solution has a profound effect on soil

hydraulic properties (Childs 1969). Many studies such as Quirk and Scofield (1955); Gardner et al. (1959); McNeal and Coleman (1966); McNeal et al. (1968); Waldron and Constantin (1968); Rhoades and Ingvalson (1969); Felhendler et al. (1974); Dane and Klute (1977); Russo and Bresler (1977a); Russo and Bresler (1977b); Dane (1978) and Frenkel et al. (1978) have been conducted in an attempt to understand the effect of sodium on soil hydraulic conductivity in both saturated and unsaturated flow.

Studies on the effects of solutions on soil hydraulic conductivity present data as relative hydraulic conductivity (RHC) versus solution concentration at a given SAR (McNeal and Coleman 1966) or a given ESP (Rowell et al. 1969); or as RHC versus ESP (Yaron and Thomas 1968) or SAR (Felhendler et al. 1974) at a given solution concentration. RHC is the ratio of hydraulic conductivity of the treated soil to the hydraulic conductivity of the untreated soil. The studies show, eg. Quirk and Scofield (1955), that a critical solution concentration exists for a given ESP and once this critical concentration is reached, the hydraulic conductivity decreases with increasing ESP of the soil (Frenkel et al. 1978). Thus, for a given solution concentration, there is a value of solution SAR or equilibrium ESP above which water movement in the soil will decrease and be controlled by the sodium status of the soil.

McNeal and Coleman (1966) found that the hydraulic conductivity decline for several soils showed similarly

shaped curves although the values were not the same for different soils. The sigmoid curves are typical of plots of similar data (McNeal 1968) and appear in other published works (van Schaik 1967; Rowell et al. 1969; Felhendler et al. 1974). Based on these studies, the author has developed a generalized curve showing the decrease in hydraulic conductivity as the sodium level in the soil increases (Figure 1).

The typical curve for hydraulic conductivity decline (Figure 1) exhibits three regions. The upper area shows little change in hydraulic conductivity with increasing sodium status until it reaches a critical value for a constant solution concentration. The second region exhibits strong control of the hydraulic conductivity by the solution SAR or soil ESP and RHC declines with increasing sodium levels. The final region again shows little effect of the sodium on the water movement since the RHC is near the minimum value possible at the solution concentration.

The second region of the hydraulic conductivity decline curve is the most important in understanding water flow reduction caused by sodium adsorption. Rowell et al. (1969) noted that hydraulic conductivity decreases at the same concentration as swelling begins and changes in the hydraulic conductivity are controlled by swelling until dispersion of the soil particles occur. The sloping region of the sigmoid curve would indicate the range over which swelling occurs.

At high ESP values, irreversible particle rearrange-

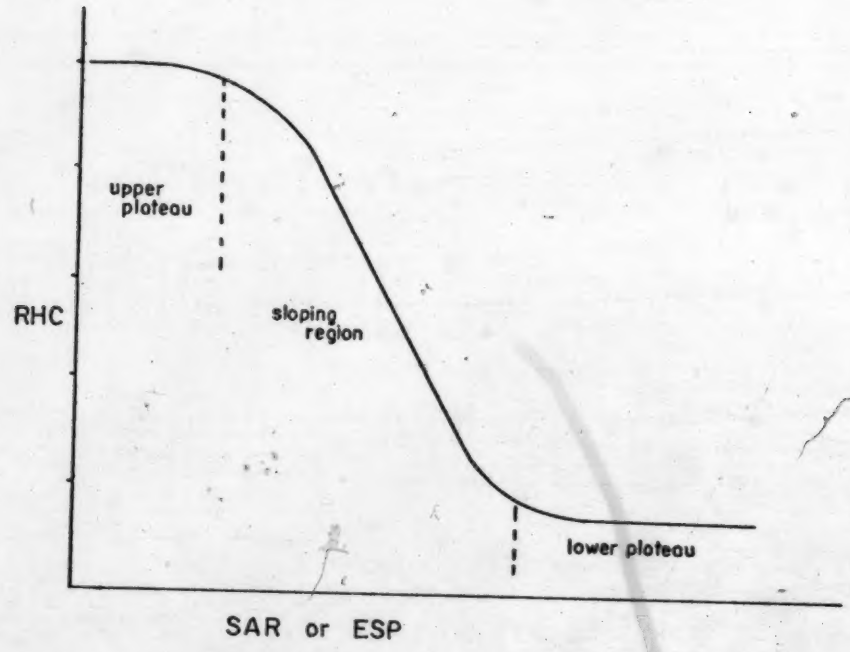

Figure 1. Relative hydraulic conductivity decline curve

ment caused by aggregate failure and dispersion occurs, severely limiting the rate of water flow by blocking the soil pores. Above a certain sodium level, flow approaches a minimum value which is reflected in the lower plateau of the sigmoid hydraulic conductivity decline curve.

The rate of decline of the RHC i.e. the slope of the near linear portion of the sigmoid curve, gives an indication of the range of values over which the adsorbed sodium exerts control on water movement. Where the control is relatively narrow, the rate of decline of hydraulic conductivity is quite rapid. The data of van Schaik (1967) in Figure 2 show this situation very well. For soils with little or no gypsum, the RHC begins to decrease at an ESP of about 5 and reaches a minimum RHC value of 0 in a range of ESP from 15 to 20. The soils containing gypsum and having a high electrolyte concentration exhibited a similar decline in RHC over a range of ESP values that are twice that of the previous soils. Saturated water movement begins to decrease at an ESP of 10 and continues until a range of ESP from 30 to 40.

Studies of the effect of sodium on unsaturated flow in soils give similar results as shown for saturated soils. The hydraulic conductivity curves presented in Figure 3 (Russo and Bresler 1977b) have a shape similar to those of the saturated soils of McNeal and Coleman (1966) and others, although the soils show greater sensitivity to sodium as saturation is approached. The smaller decrease of

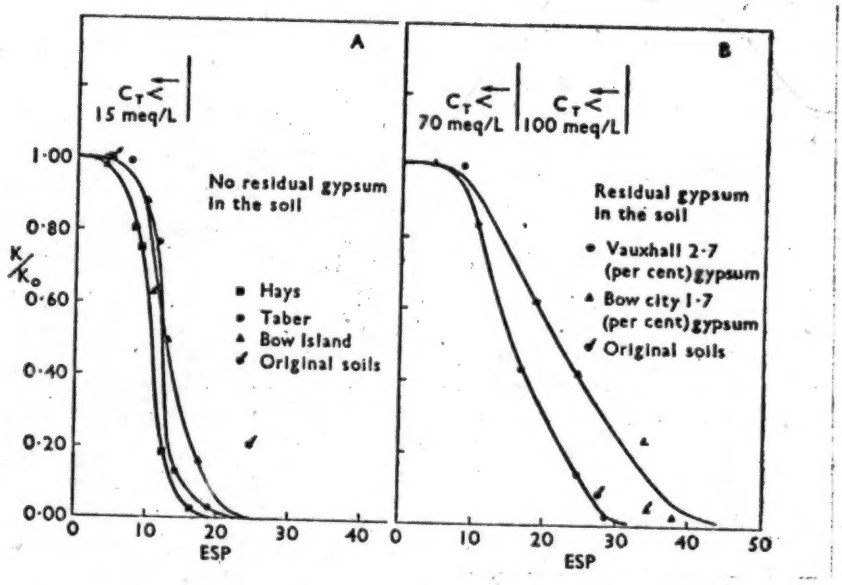

Figure 2. Relative hydraulic conductivity (K/K_o) as a function of ESP for a) soils containing no gypsum and b) soils containing gypsum. C_T indicates the total electrolyte concentration in the soil extract (van Schaik 1967)

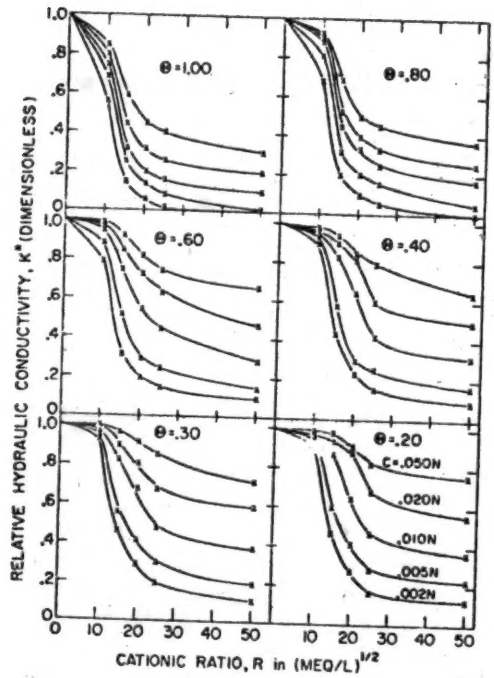

Figure 3. Relative hydraulic conductivity as a function of cationic ratio (R) and solution concentration (C) for six water contents (θ) (Russo and Bresler 1977b)

hydraulic conductivity with increasing SAR at lower moisture contents is attributed to less clay swelling and possibly a reduction in irreversible particle rearrangement such as pore blocking by clay movement (Russo and Bresler 1977b). The data from Figure 3 indicate that a higher sodium level may be tolerated in the soil for a given solution concentration if the moisture content is lowered.

Studies of the diffusivity of water in unsaturated soils show similar results as the hydraulic conductivity experiments. Gardner et al. (1959) noted that most of the reduction of water diffusivity was due to decreases under near saturated conditions, but water movement was affected at all moisture contents. It was concluded that exchangeable sodium has an effect on the hydraulic properties of a soil for all levels of water saturation especially at low solution concentration levels. Christenson and Ferguson (1966) showed that the diffusivity of a low concentration calcium solution was higher than that of distilled water at high moisture contents but the difference between the movement of the two fluids was negligible at low moisture levels. The differences in diffusivity of the calcium solution and distilled water was attributed to differences in the thickness of the double layer and the amount of swelling of the soil samples (Christenson and Ferguson 1966).

Another measurement of water movement is the infiltration of water into a soil. Capillary rise is the

infiltration vertically upward into a soil. van Schaik and Cairns (1969) measured the height of capillarity of sodium sulphate solution into the A horizon of a Duagh Solonetz after contact with the solution for 72 hours. The data as plotted by the author in Figure 4 depict a sigmoid curve. The curve is the reverse of the hydraulic conductivity curve since the effect of sodium is reduced as the solution concentration increases. Despite the change of direction, similar regions are evident. There is a significant decline in the water uptake from 0.1N to 0.02N sodium. Above and below that concentration range, there is less change in capillary rise with change in solution concentration. Other experiments show that for the Duagh Solonetz, wetting by vertical downward infiltration and capillarity provide similar results (Cairns and van Schaik 1968). Therefore, the matric potential is the driving force in water movement in this soil and the effect of gravity potential is minimal.

Most of the studies previously noted use equilibrium solutions to determine the effect of sodium on water movement but few experiments show the effect of very low concentration solutions such as good quality irrigation water or rainfall on hydraulic conductivity of the soil. It is the flow of these solutions through soils, even moderately affected by sodium, that is a common problem (Frenkel et al. 1978). This is the case for most Solonetzic soils especially where rainfall or snowmelt are the only sources of moisture. Since the interaction of the fluid and the soil medium

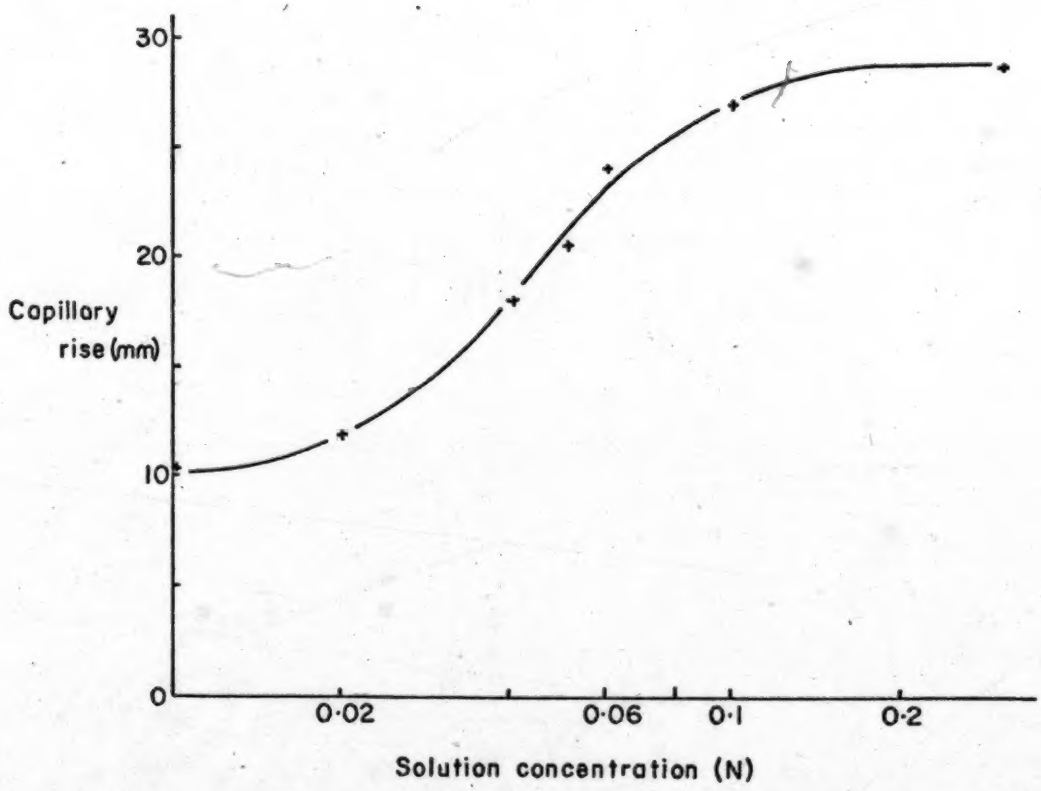

Figure 4. Capillary rise of Na_2SO_4 solution into the A horizon of a Duagh Solonetz after 72 hours (data from van Schaik and Cairns 1969)

depends partially on the concentration of the solution, pure water should provide the most disruptive influence on a sodium affected soil system. Fireman (1944) felt that due to the hydrophilic nature of the colloidal portion of the soil, only water should be used to study soil hydraulic properties.

The soils studied by Felhendler et al. (1974) showed a decline in hydraulic conductivity when water was used in place of equilibrium solutions. In particular, the sandy loam (Natanya) shown in Figure 5, which had been equilibrated with a solution of an SAR value of 10 exhibited hydraulic conductivity values of practically zero when distilled water replaced the salt solution. The same soil showed no decrease in hydraulic conductivity until the SAR reached 15 when the fluid had a concentration of 0.01N. In all cases, the hydraulic conductivity was lower for an equilibrium SAR when the concentration of the solution was reduced to zero.

Christenson and Ferguson (1966) showed decreases in unsaturated water flow at an ESP as low as 5.5 when distilled water was used. The slow rate of wetting was attributed to swelling caused by the low solution concentration. In order to observe the effect of water of low concentration on flow in soils affected with sodium, distilled water will give an indication of the maximum reduction in flow.

The review of literature indicates that many

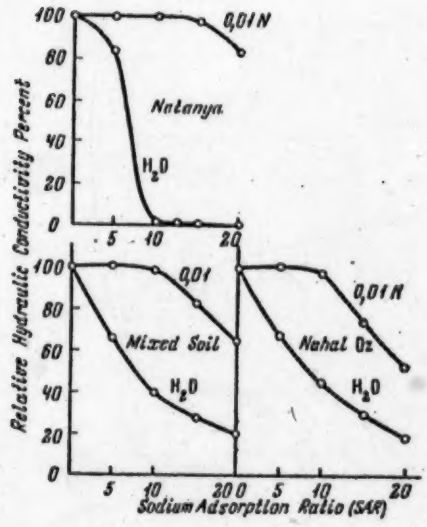

Figure 5. Relative hydraulic conductivity as a function of SAR and the concentration of the leaching solution (Felhendler et al. 1974)

factors control the rate of water movement in a soil. Intrinsic soil characteristics such as the type and amount of clay as well as the level of organic matter have a great influence on the manner in which the soil medium will react to the soil solution. Although the soil solution composition and concentration cannot fully explain hydraulic conductivity behavior of soils (McNeal and Coleman 1966; Russo and Bresler 1977b), within a certain range, the soil chemical characteristics exhibit strong influence on hydraulic conductivity for a given soil. It is in this range that the interaction is important in determining or predicting soil hydraulic conductivities. Attempts to model hydraulic conductivity change in a soil with changing percolating solutions (McNeal 1968; Lagerwerff et al. 1969; Dane 1978) have not been successful in eliminating the need for an initial hydraulic conductivity measurement (Dane 1978) to help determine the soil-fluid interaction. Since many factors control water movement in soils, the relationship of adsorbed sodium and soil hydraulic conductivity must be measured for any particular soil (McNeal and Coleman 1966; Thomas and Yaron 1968; Rhoades and Ingvalson 1969; Frenkel et al. 1978).

3. MATERIALS AND METHODS

3.1 Soils

The soils used in this study were sampled from plots on the Agriculture Canada Substation at Vegreville in East-Central Alberta. The area has been mapped as a complex of Solonetzic and Chernozemic soils developed on fine-textured lacustrine materials. The soil series represented in the sampling area include the Duagh SiL, a Black Solonetz; the Wetaskiwin SiL, a Black Solodized Solonetz; and the Malmo SiL, an Eluviated Black Chernozem. Detailed profile descriptions are presented in Appendix 7.2.

Bowser et al. (1962) found that the three soils form a catena where the Malmo occupies the better drained upslope position and the Duagh is found in the lower, poorer drained areas. The Wetaskiwin soil is the intermediate member of the complex and is developed between the Duagh and the Malmo soils. Cairns (1961) noted that the Duagh soil can be found surrounding small pockets of the Malmo soil with apparently little regard for topographic position. Although there were little topographic differences within the sampled areas, the three profiles were found to be intermixed.

The soils were sampled from plots that had been prepared and maintained by the staff of the Agriculture Canada Substation at Vegreville. Two sets of plots treated with chemical amendments were used to procure samples for the study in order to maximize the range of chemical properties

of the samples. Although the soil had a high degree of natural variability, it was intended that further treatment by chemical amendments may provide samples with a wide range of adsorbed sodium levels.

The first set of plots (Experiment 1) had been treated with a variety of nitrate salts at the rate of 60 kg/ha of nitrogen annually for seven years (1970 - 1976). The second set (Experiment II) had treatments of sodium and/or ammonium salts at the rate of 146 kg/ha of sodium and/or 89 kg/ha of nitrogen annually for six years (1971 - 1976). The treatments are described in more detail in Table 2. A check plot was maintained for both sets of treatments and all checks and treatments were triplicated in a randomized block design. The plots were cropped with bromegrass and harvested annually.

In Experiment I, the salts of nitrate had accompanying cations of calcium, potassium, ammonium and barium. Since these cations are more strongly adsorbed than sodium (Table 1), they should displace the sodium from the exchange complex and consequently lower the level of adsorbed sodium in the soil. The treatment of the soils with sodium in Experiment II should increase the level of sodium within the profile. This should provide a wide range of adsorbed sodium values to study the effects of added sodium on the soil profile.

Since is was thought that the amendments in both experiments would alter the chemistry of the soils and consequently the rate of water movement, the soils were

TABLE 2

TREATMENTS ON PLOTS

TREATMENT	ELEMENT (Ionic Form) kg/ha					
	$N(NO_3^-)$	$N(NH_4^+)$	$Na(Na^+)$	$S(SO_4^=)$	$Cl(Cl^-)$	OTHER
EXPERIMENT I						
1. CHECK (I)	---	---	---	---	---	-----
2. $Ca(NO_3)_2$	60	---	---	---	---	86 (Ca^{++})
3. KNO_3	60	---	---	---	---	168 (K^+)
4. NH_4NO_3	30	30	---	---	---	-----
5. $Ba(NO_3)_2$	60	---	---	---	---	294 (Ba^{++})
EXPERIMENT II						
6. CHECK (II)	---	---	---	---	---	-----
7. NH_4NO_3	44.5	44.5	---	---	---	-----
8. NH_4Cl	---	89	---	---	226	-----
9. NaCl	---	---	146	---	226	-----
10. Na_2SO_4	---	---	146	102	---	-----
11. NaCl + NH_4NO_3	44.5	44.5	146	---	226	-----
12. Na_2SO_4 + NH_4NO_3	44.5	44.5	146	102	---	-----

sampled for chemical analysis and water movement studies. A sample from each of the A and B horizons was taken from each replicate of the treatments. All samples were air dried and ground by roller grinder to pass a 2 mm sieve.

3.2 Soil analysis

The soil samples were analyzed by several chemical tests as outlined by McKeague (1976). The concentration of the cations of calcium, magnesium, sodium and potassium in the various extracts were determined by atomic adsorption spectrophotometry. The electrical conductivity and the concentration of the cations in the saturated paste extract were measured. The ammonium acetate extractable cations of calcium, magnesium, sodium and potassium were measured. The Cation Exchange Capacity (CEC) was determined by the sodium acetate method. The exchangeable cations were determined by subtraction of the soluble cations from the extractable cations.

The Sodium Adsorption Ratio (SAR) was calculated for each sample by

$$SAR = \frac{[Na]}{\left[\frac{Ca + Mg}{2}\right]^{\frac{1}{2}}}$$

where the concentration of the cations from the saturation paste extract were determined in meq/L. The Exchangeable Sodium Ratio (ESR) was calculated for each sample by

$$ESR = \frac{Na\ (ads)}{CEC - Na\ (ads)}$$

where Na (ads) is the exchangeable sodium in meq/100 g and the CEC is measured in meq/100 g.

Other chemical tests from McKeague (1976) included the pH of the 2.5:1, water: soil suspension and the organic carbon content. The percentage carbon in the samples was determined using the LECO furnace. Carbonates were not determined since non of the samples showed effervescence when treated with 10% hydrochloric acid. Therefore, all of the carbon was considered to be from organic matter and the percentage carbon could be used as a measure of the organic matter level in the soil.

The particle size distribution of each sample was determined by the hydrometer method outlined by McKeague (1976). The particle size classes and the textural classes were defined according to the guidelines of the Canada Soil Survey Committee (1978).

3.3 Hydraulic conductivity

Saturated hydraulic conductivity measurements were performed on the disturbed samples according to a method similar to that outlined by Reeve and Brooks (1953). The notable deviations from the method were that air dried 2 mm soil samples were used in accordance to the methods of Fireman (1944) and Richards (1954) and the samples were placed into the permeameters by the use of a tremie funnel.

The permeameters (Figure 6) consisted of a copper cylinder that was 7.7 cm in length and 7.6 cm in diameter.

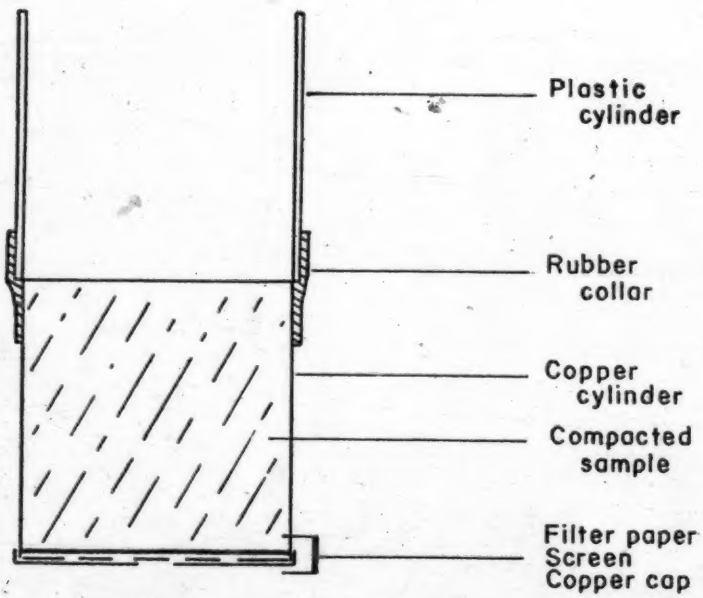

Figure 6. Permeameters for hydraulic conductivity measurements on disturbed samples

The base of the cylinder was a copper cap with a hole approximately 1 cm in diameter in the center. The base supported an aluminum screen and a filter paper.

A plastic cylinder of equal length and inside diameter was placed on the copper cylinder and attached with a rubber collar. The cylinders were filled with soil to about three-quarters of the combined height. The soil was compacted by the use of a tamping apparatus which dropped the cylinder 200 times from a height of 1.3 cm with a 1 kg block on the sample. The plastic cylinder was removed and the soil leveled with a spatula. The mass of the soil was measured to determine the density of the packed sample.

The soils were allowed to saturate with distilled water by capillarity from the bottom of the cylinder. Once saturation was achieved, a hydraulic gradient of approximately two was maintained by ponding on the soil surface which was protected by a filter paper. The effluent that passed through the column was collected. All measurements were made in triplicate.

The saturated hydraulic conductivity was determined by Darcy's equation,

$$K = \frac{Q\,L}{H\,A\,t}$$

where

K = hydraulic conductivity (cm/hr)

Q = volume of effluent (cm^3)

L = flow length (Height of column) (cm)

H = hydraulic head (cm)

A = cross sectional area of column (cm^2)

t = time to collect Q (hr)

3.4 Laboratory infiltration

Water infiltration measurements were performed in the laboratory on disturbed samples of the A and B horizons. Water was allowed to penetrate the sample by capillarity from a free water surface. The measurement was the volume of water absorbed over set time intervals.

The apparatus for the water infiltration was designed as suggested by Dr. A.N. Al-Ani, Visiting Professor, University of Baghdad, Iraq (personal communication). The apparatus (Figure 7) consisted of a 50 mL buret connected by a valved tube to the base of a Buchner funnel. The Buchner funnel was 2.5 cm in height and 4.5 cm in diameter and was removable from the tapered base.

The hydraulic head was controlled by a capillary at the base of the buret. The capillary was set so that the hydraulic head at the bottom of the soil sample in the Buchner funnel was zero. The driving force for the water movement was therefore the matric potential of the dry sample. Air was drawn into the buret through the capillary to replace the volume of water that entered the soil sample.

A soil sample splitter was used to divide the samples four ways and each sub-sample was packed into the Buchner funnel by vibration. Vibration was provided by the use of an electric engraver without a tip. The vibrating end was placed in contact with the side of the Buchner

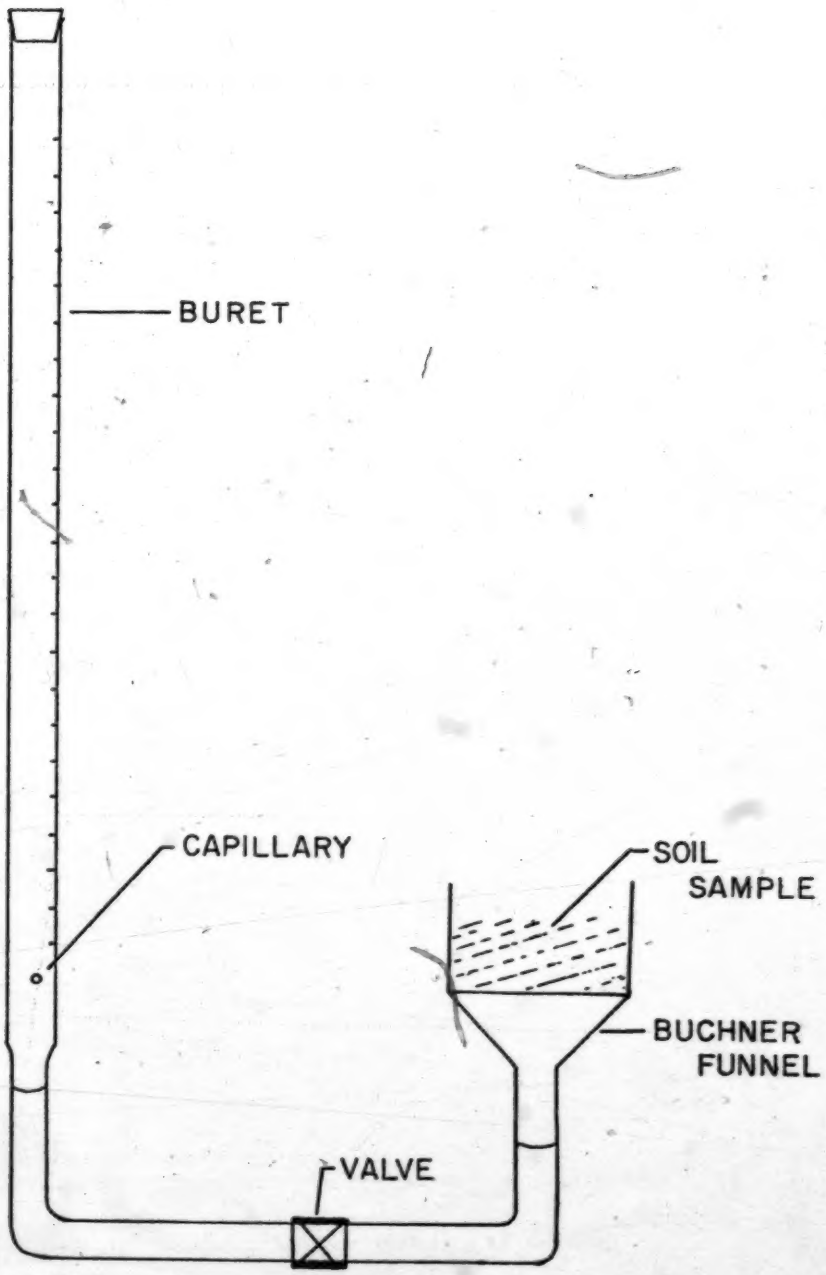

Figure 7. Apparatus for laboratory infiltration studies

funnel and the funnel was rotated once. A paper filter prevented the sample from passing through the funnel. Each sample was run in quadruplicate. The amount of water absorbed by the soil sample was measured at time intervals of 2, 5, 10, 20, 40, 60, 90, 120 and 180 minutes.

The infiltration data were fitted to the cumulative infiltration equation,

$$I = ct^a$$

where I = cumulative infiltration (mL)

t = time (min)

c and a = empirical constants.

4. RESULTS AND DISCUSSION

4.1 Relationship between SAR and ESP

It is desirable that the cations on the exchange complex can be expressed by analysis of a water extract at equilibrium conditions. The Exchangeable Sodium Ratio (ESR) has been shown to be proportional to the Sodium Adsorption Ratio (SAR) (Richards 1954). Therefore, if the relationship between the ESR and SAR can be determined, the SAR could be used to express the exchangeable sodium status of the soil. Since the relationship between ESR and SAR is related to intrinsic soil properties (Poonia and Talibudeen 1977), it is expected that significantly different soils will have unique relationships between the soluble and exchangeable phases.

The means for the soil properties listed in Table 3 indicate that the soil properties are different between the A and B horizons. Further analyses by paired t-tests show this to be true (Appendix 7.4.1). The mean for each property in the A horizon is highly significantly different from the corresponding value in the B horizon. The carbon, sand and silt contents as well as the Cation Exchange Capacity (CEC) are significantly higher in the A horizon than in the B horizon. The remaining properties including the clay content, pH, SAR and Electrical Conductivity (EC) are significantly greater in the B horizon than the A horizon.

The A horizon has an organic carbon content that

TABLE 3

MEAN VALUES AND RANGES FOR CERTAIN PROPERTIES OF 35 SAMPLES FROM A DUAGH-MALMO SOILS COMPLEX

A Horizon		Mean	Range
carbon	%	5.10	3.98 - 7.32
texture		SiL	SiL
clay	%	21	17 - 25
sand	%	16	9 - 23
silt	%	63	51 - 70
pH		5.5	4.4 - 6.1
CEC	meq/100g	39.3	26.4 - 57.1
SAR		5.5	0.2 - 16.9
E.C.	S/m	0.080	0.022 - 0.14

B Horizon		Mean	Range
carbon	%	1.37	0.71 - 2.19
texture		SiC	SiCL - SiC
clay	%	44	25 - 53
sand	%	6	0 - 14
silt	%	50	43 - 65
pH		6.3	5.2 - 7.6
CEC	meq/100g	34.4	14.9 - 47.3
SAR		12.3	1.7 - 33.1
E.C.	S/m	0.29	0.02 - 0.92

is 3.7 times greater than the carbon content for the B horizon. The textures of the two horizons are also significantly different. The A horizon samples all fall into the textural class of SiL but the B horizon samples averaged as a SiC and ranged from SiCL to SiC. The important point is that the clay content in the B horizon is twice as large as that in the A horizon.

The clay and organic matter contents are the most important soil properties in determining the exchange characteristics of a soil, since these are the most surficially active of the soil components. It is not surprising, considering the large differences in organic matter and clay contents between the horizons, that there would be a significant difference in the CEC between the A and B horizons. Since the two soil horizons have different soil properties, especially in terms of factors that affect the exchange material, differences in the rates of adsorption of exchangeable cations may be expected for the horizons.

In order to determine the rate of adsorption of sodium in the two soil horizons, a regression analysis of ESR on SAR was conducted for the data of the A and B horizons. The regression equation for the A horizon is

$$ESR = 0.0076 + 0.0058\ SAR$$

and for the B horizon is

$$ESR = -.0180 + 0.0173\ SAR.$$

The equations for both horizons are plotted in Figure 8. The ESR is highly significantly correlated to the SAR (r^2 =

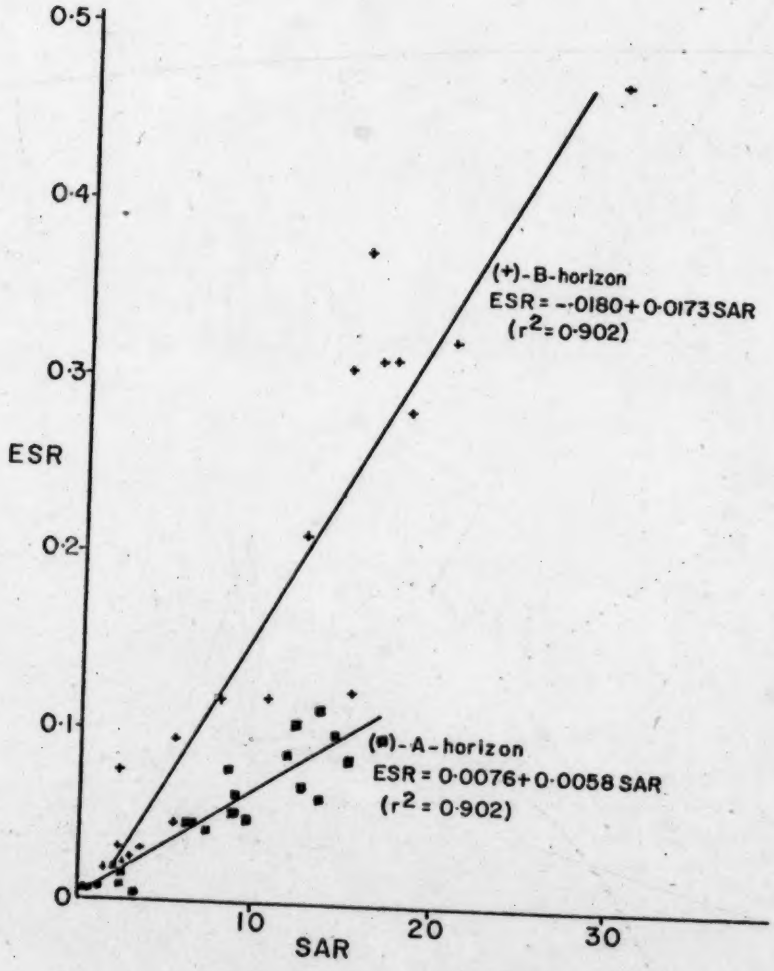

Figure 8. ESR as a function of SAR for the A and B horizons of a Duagh-Malmo soils complex

0.902) for both of the soil horizons. Since a linear relationship between ESR and SAR has been previously recognized (Richards 1954), this high correlation was expected. The correlation of ESR and SAR in this study compares well to other studies. In a comparison of such regressions, presented in Table 4, the CL soil of Paliwal and Gandhi (1976) has a slightly larger coefficient of determination for the regression than the soil of the present study.

Although both horizons have the same level of correlation between ESR and SAR, the regression equations are quite different. An analysis of the variances of the two regressions indicates that the data for the two horizons are from different populations. The complete analysis of variance is presented in Appendix 7.4.2. It was previously noted that the means of SAR for the A and B horizons are significantly different (Table 3). It is therefore concluded that the coefficients for the regression of ESR on SAR in the A and B horizons are for significantly different functions.

It was discussed earlier that the proportionality constant for the relationship between ESR and SAR can be compared to the exchange constant of the Gapon equation. The slope of the regression equation is therefore comparable to the exchange constant. Since the slope of the regression for the B horizon (0.0173) is almost three times the same value for the A horizon (0.0058), the exchange constant for the B horizon is thrice that of the A horizon. This means

TABLE 4

COMPARISON OF ESR-SAR REGRESSIONS

SOIL	REGRESSION LINE	r^2	REFERENCE
A Horizon	ESR= .0076+.0058 SAR	.902	
B Horizon	ESR=-.0180+.0173 SAR	.902	
59 soils from western USA	ESR= .0126+.01475 SAR	.852	(Richards 1954)
LS	ESR= .1593+.0074 SAR	.839	(Paliwal and Gandhi 1976)
SCL	ESR= .1324+.0109 SAR	.834	
CL	ESR= .1320+.0152 SAR	.918	
above 3 soils combined	ESR= .1149+.0109 SAR	.792	

that a unit increase in SAR will result in an increase in ESR that is three times greater in the B horizon than in the A horizon.

A significant factor in accounting for the differences in exchange constants is the difference in the organic matter content between the horizons. The A horizon has nearly four times more organic carbon than the B horizon. Poonia and Talibudeen (1977) noted a preference for calcium adsorption in the upper horizons compared to corresponding subsoils. They attributed the differences in ion adsorption to high amounts of organic matter in the surface soils since organic matter has been shown to have a strong preference for divalent cations, especially calcium (Salmon 1964). Because of its preferential adsorption of divalent cations, an increase in organic matter will decrease the exchange constant for sodium.

By comparing the relationship of ESR and SAR for the other soils in Table 4, it is noticeable from the data of Paliwal and Gandhi (1976) that the amount of clay is also significant in affecting the exchange constant. The slope of the regression line increases with increasing clay content. This trend carries on with the fine textured (SiC) B horizon which has a steeper slope than the other soils. Sodium adsorption increases as the amount of clay in the soil increases.

The two properties that exhibit large differences between the two horizons, i.e. clay and organic matter contents, are operating in opposite directions with respect to sodium

adsorption. The result is that the differences between the exchange constants for the A and B horizons widens greatly. The difference in the adsorption of sodium between the horizons shows the dependence of the relationship between ESR and SAR on the other soil properties. Significant differences in the soil properties, especially those related to the exchange complex are reflected in the relationship between ESR and SAR.

The dependence of the relationship between ESR and SAR on other soil properties brings to question the adequacy of the equation relating ESR and SAR developed by Richards (1954). This equation, presented in Table 4, is based on a composite of 59 surface soils and does not consider differences in soil properties. The equation for the B horizon is similar to Richards' equation but the A horizon equation is quite different. The equation developed by Richards (1954) relating ESR and SAR is not suitable to account for sodium adsorption in the A horizon of a Duagh-Malmo soils complex. Since the relationship of SAR and ESR is dependent on soil properties, especially the amounts of clay and organic matter, then the relationship should be determined for soils that differ significantly in these properties.

Since the ESR and the Exchangeable Sodium Percentage (ESP) are mathematically related by

$$ESP = \frac{ESR\ (100)}{1 + ESR},$$

the ESP can be expressed in terms of the SAR with the same

level of significance as the linear regression of the ESR and SAR. Therefore, the ESP and SAR are highly significantly correlated through the following curvilinear relationships for the A horizon,

$$ESP = \frac{(0.0076 + 0.0058\ SAR)\ 100}{1 + (0.0076 + 0.0058\ SAR)}$$

and the B horizon,

$$ESP = \frac{(-.0180 + 0.0173\ SAR)\ 100}{1 + (-.0180 + 0.0173\ SAR)}.$$

The equations relating the ESP to the SAR for both horizons are depicted in Figure 9. The high correlation between SAR and ESP means that 90% of the variation in exchangeable sodium can be explained by the soluble cations of a water extract. The overall variation in the relationship between SAR and ESP is sufficiently small to warrant the use of the SAR of the saturated paste extract as a measurement of the exchangeable sodium level in the Duagh Solonetz and associated soils. The appropriate equation must be used for each horizon.

4.2 Effects of treatments on sodium levels

The major chemical criterium to determine whether a soil belongs to the Solonetzic Order is the ratio of exchangeable calcium to exchangeable sodium (ExCa:Na). A soil that shows the characteristic solonetzic morphology and has a ratio of ExCa:Na in the B horizon of less than ten falls in the category of Solonetzic Soils. Since it has been shown that the SAR is related to the exchangeable cation levels, it would be useful to determine the SAR value that corresponds

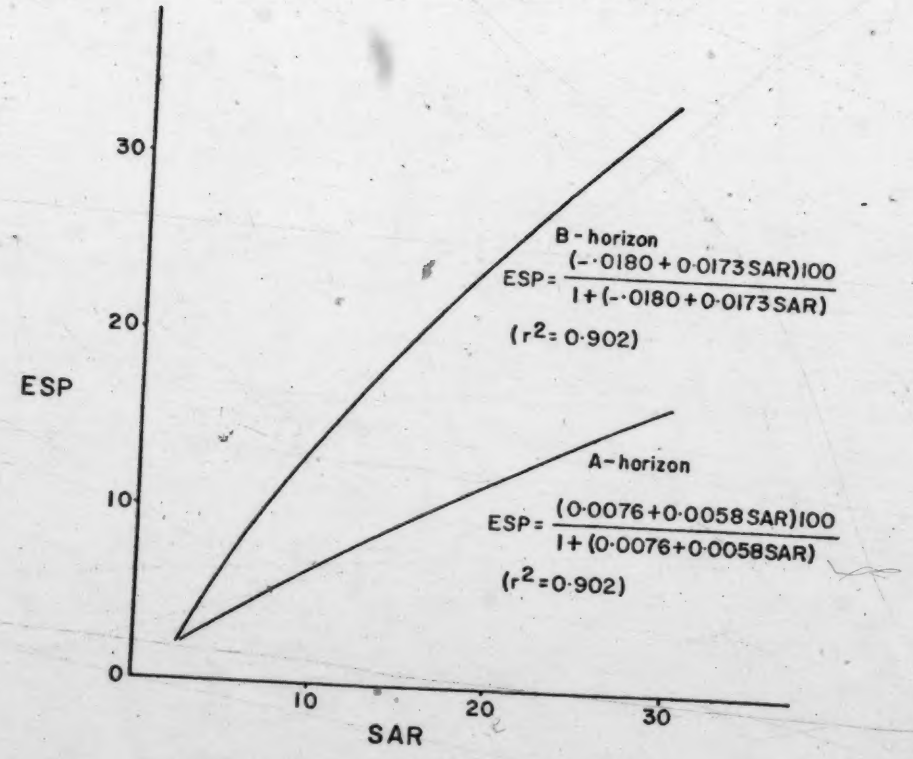

Figure 9. ESP as a function of SAR for the A and B horizons of a Duagh-Malmo soils complex

to the boundary between Solonetzic and non-Solonetzic Soils.

A log x log transformation of the data for SAR and ExCa:Na in the B horizon results in a reasonably linear relationship. The regression of log (ExCa:Na) on log (SAR) provides the function,

log (ExCa:Na) = 1.645 - 1.34 log SAR which is which is transformed to

$$ExCa:Na = 44.2\ SAR^{-1.34}$$

and is plotted in Figure 10. The regression equation has a high level of explained variation ($r^2 = 0.925$) which is similar to the variability in the relationship for ESP and SAR.

Because the relationship is strongly linear, the data points fall either in the quadrants (ExCa:Na < 10, SAR > 3) or (ExCa:Na > 10, SAR < 3). Since ExCa:Na of ten in the Bnt horizon is the cutoff value for Solonetzic soils, likewise, the SAR value of three should represent the same cutoff point. All soils which have an SAR of less than three in the B horizon should belong to the non-Solonetzic soils that are represented by the Malmo series, an Eluviated Black Chernozem. The samples in the group where the SAR is greater than three would be from profiles that belong to the Solonetzic Order represented by the Wetaskiwin and Duagh series of Black Solodized Solonetz and Black Solonetz respectively. This corresponds to a field inspection of the sampling sites. Therefore, for the Duagh, Wetaskiwin, Malmo soil association, an SAR of three in the B horizon can be

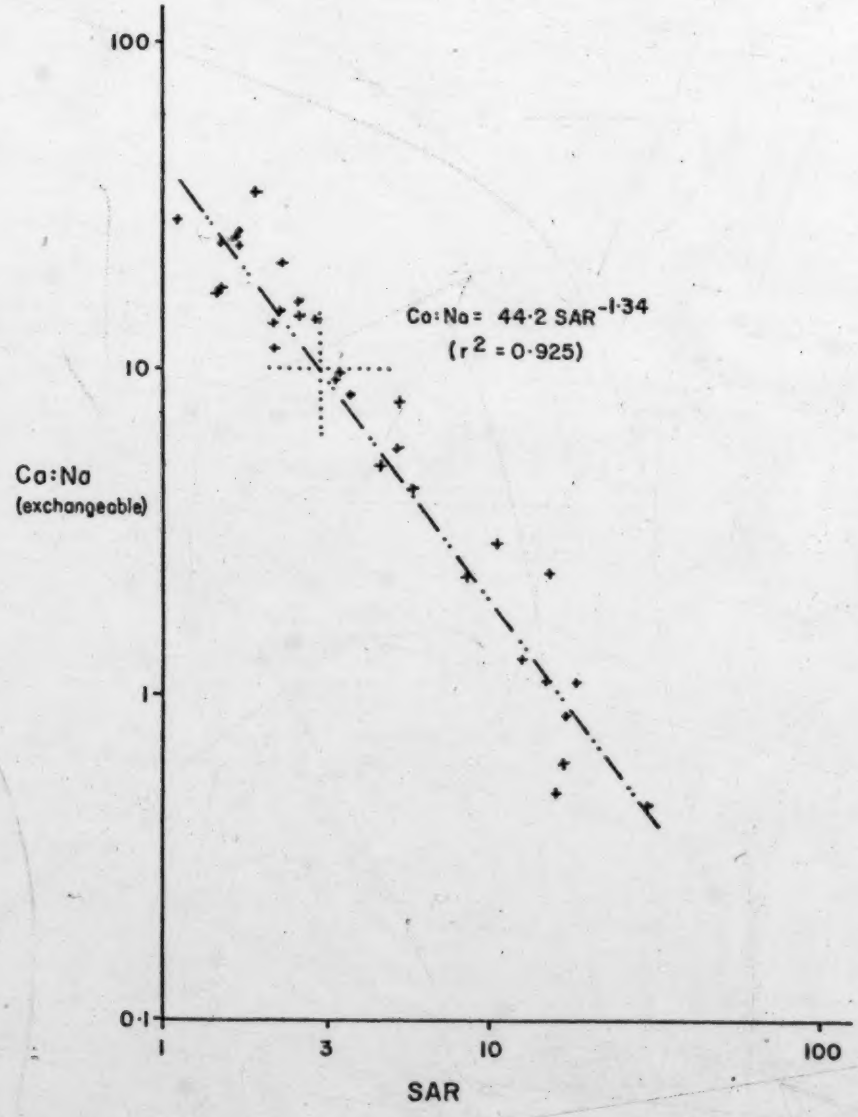

Figure 10. Exchangeable calcium-sodium ratio as a function of SAR for the B horizon of a Duagh-Malmo soils complex

considered the cutoff point that corresponds to the ExCa:Na of ten that separates the Solonetzic and Chernozemic soils.

Since the ExCa:Na is a measurement of the degree of "Solonetzicity" and the SAR can be used to represent that value, a study of the levels of SAR in the soil was conducted to determine whether the treatments on the plots had any effect on the level of adsorbed sodium in the soil. In accordance with the relationship of SAR and ExCa:Na, analyses of variances were performed on the logarithmic transformation of the SAR data. A summary of the treatment geometric means is presented in Table 5 and the complete analyses of variances is provided in Appendix 7.4.3. The effects of the chemical amendments in both sets of treatments were determined for the A and B horizons.

As noted in Table 5, there are no significant differences in the SAR of the B horizon for any of the treatments. Likewise, the treatments do not significantly affect the SAR of the A horizon in Experiment I. The only analyses where significant differences in the SAR occur is in the A horizon of Experiment II. The nitrogen only treatments (NH_4NO_3 and NH_4Cl) have significantly lower SAR values than the check and the sodium treatments with or without nitrogen (Table 5). Although there is a trend for the sodium treatments to increase the level of sodium in the A horizon of Experiment II the differences, when compared to the check, are not significant.

The natural variability of sodium in Solonetzic

TABLE 5

EFFECT OF TREATMENT ON THE SAR OF A AND B HORIZONS OF A DUAGH-MALMO SOILS COMPLEX

TREATMENT	SAR[1]	
	A HORIZON	B HORIZON
Experiment I		
KNO_3	0.36 a	1.6 b
$Ba(NO_3)_2$	0.39 a	3.4 b
$Ca(NO_3)_2$	0.72 a	4.3 b
NH_4NO_3	0.86 a	4.7 b
Check (I)	1.25 a	5.2 b
Experiment II		
NH_4Cl	2.0 c	18.0 e
NH_4NO_3	2.6 c	12.3 e
Check (II)	6.8 d	11.9 e
$NaCl + NH_4NO_3$	9.2 d	10.0 e
$Na_2SO_4 + NH_4NO_3$	11.2 d	9.7 e
NaCl	11.4 d	17.5 e
Na_2SO_4	11.5 d	24.1 e

[1] SAR values within each horizon, for each experiment followed by the same symbol are not significantly different ($p \leq .05$). The SAR value is the geometric mean of three replicates.

soils is very high and tends to mask the effect of any treatment on the soil. Except for the effect of the nitrogen treatments on the A horizons in Experiment II, there is no significant change in the adsorbed sodium levels of the soil samples. Therefore, the samples can be used as a contiuum of sodium levels that are mainly due to the natural variability of the soil association.

4.3 Hydraulic conductivity

The disturbed hydraulic conductivity measurements show a wide variation in values. Since the range of measurements extend through five orders of magnitude, comparisons are based on a logarithmic transformation of the hydraulic conductivity values. The hydraulic conductivity (HC) is plotted on a logarithmic scale against SAR for the A horizon in Figure 11 and the B horizon in Figure 12.

The data for the B horizon samples indicate a similar curve as depicted in Figure 1. All three portions of the sigmoid curve for HC decline are quite prevalent in Figure 12. The HC remains fairly constant varying about a mean of 14.1 cm/hr until the SAR equals approximately 3. At that point, the HC begins to decline at a steady rate until the SAR exceeds 14. At the higher level of SAR, the HC values have reached the minimum values and maintain a mean of 0.001 cm/hr. Between SAR values of 3 and 14, the HC shows a dramatic decrease through four orders of magnitude.

The range of HC values between the two critical

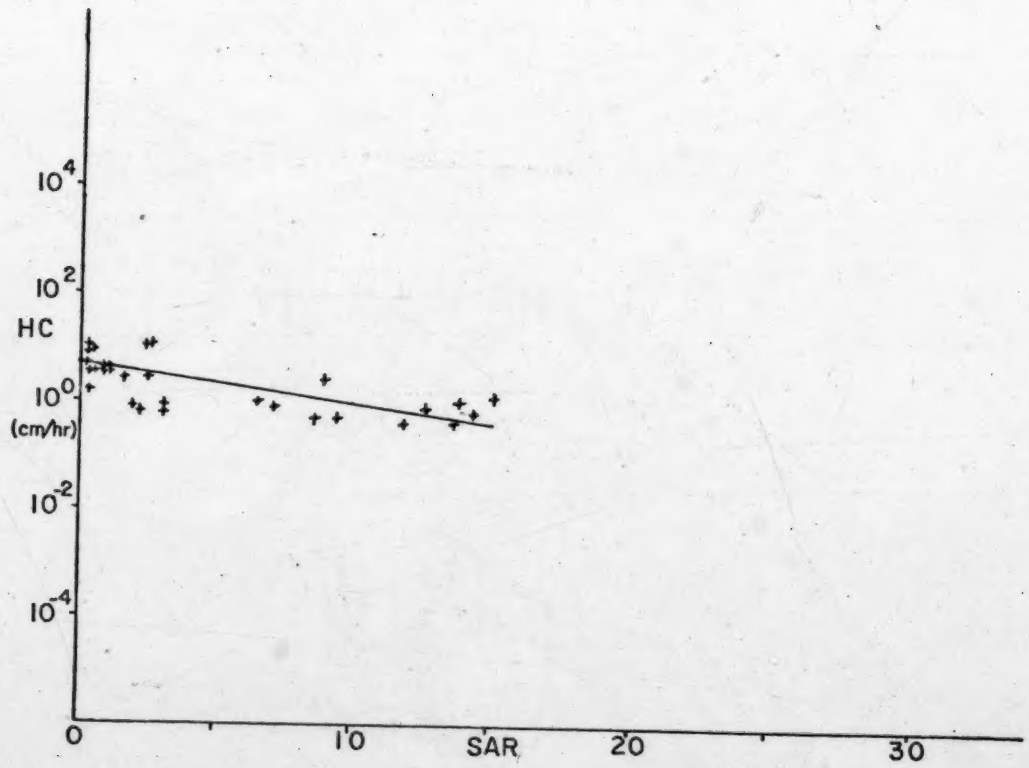

Figure 11. Hydraulic conductivity as a function of SAR for the A horizon of a Duagh-Malmo soils complex

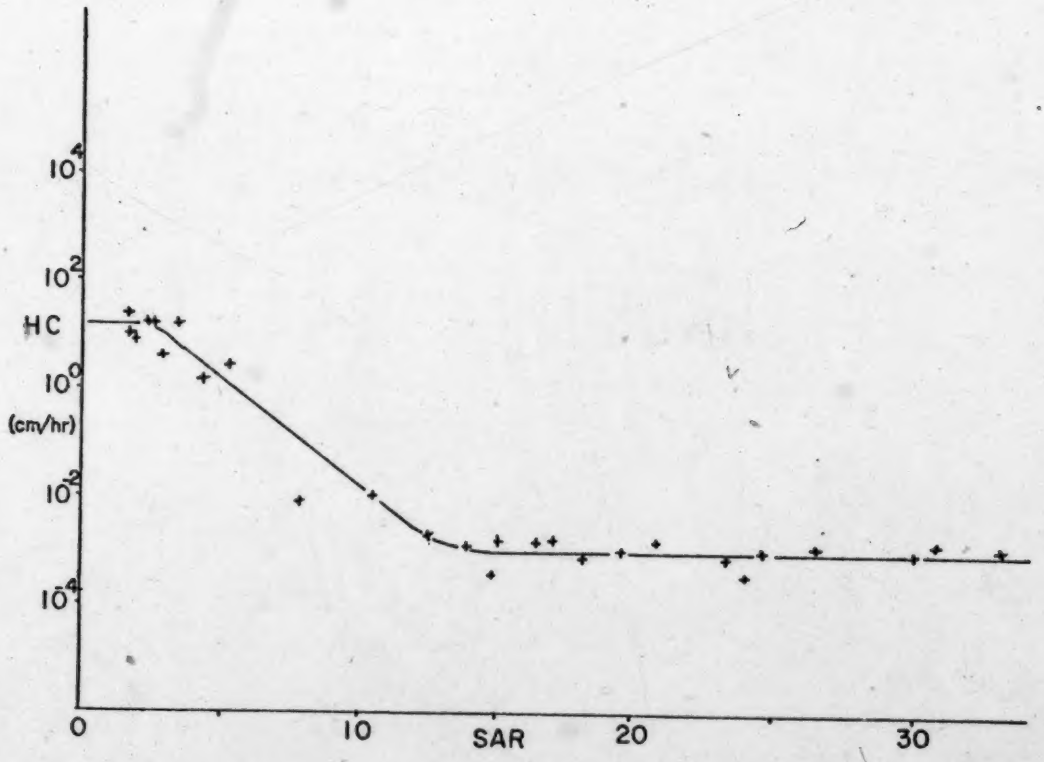

Figure 12. Hydraulic conductivity as a function of SAR for the B horizon of a Duagh-Malmo soils complex

SAR values i.e. 3 and 14, show the sloping region of the decline curve very well. Through this region, log HC is very highly correlated to the SAR (r^2 = 0.902). The high correlation value indicates that the level of adsorbed sodium has a significant effect on the HC of the soil over the range between SAR values of 3 and 14. Since over 90% of the variation in log HC can be explained in terms of the SAR, then sodium is the major component in controlling saturated water movement in this specific range. Above and below this narrow range of adsorbed sodium values the SAR does not exhibit direct control on the HC.

The hydraulic conductivity measurements in the A horizon show little change with increasing SAR. The HC decline curve as observed in the B horizon is not evident. The range of sodium levels in the A horizon of the Duagh-Malmo complex is not sufficient to show significant decreases in saturated water flow.

Part of the observation that the HC of the A horizon is not sensitive to the SAR is due to the low exchange constant for sodium in the A horizon. Although the range of SAR in the A horizon is about half of the SAR range of the B horizon, the range in ESP in the A is less than a third of the ESP range for the B. The maximum ESP in the A horizon is 9.6. An ESP value of 3 in the B horizon corresponds to an SAR of 4.6 in the A horizon for the same ESP (3.3). If the exchange constant was the only factor, the HC should be affected by an SAR level greater than 5 in the A horizon. Since this does

not exist, other factors affect the sensitivity of saturated water flow to adsorbed sodium levels in the A horizon.

The differences in the soil properties of the A compared to the B horizon must affect the SAR level at which the HC begins to decline. The significance of other soil properties especially organic matter and clay content on this relationship will be discussed further.

4.4 Laboratory infiltration

The upward water infiltration measurements were taken at set intervals over a three hour period. The cumulative infiltration values for the three hours are plotted against SAR in Figures 13 and 14 for the A and B horizons respectively.

The infiltration data for the B horizon samples (Figure 14) indicate a similar curve as depicted in Figure 1 and as shown by the hydraulic conductivity data for the same horizon (Figure 12). The sigmoid curve of water movement decline is quite evident. The cumulative infiltration for 180 min remains fairly constant varying about a mean of 12.1 mL until the SAR reaches 7. At that point, the water uptake begins to decrease at a steady rate until the SAR exceeds 21. At the higher levels of SAR, the cumulative infiltration reaches minimum values and maintains a mean of 4.0 mL.

Between the SAR values of 7 and 21, the water uptake after 180 min shows a decrease of 3 times and

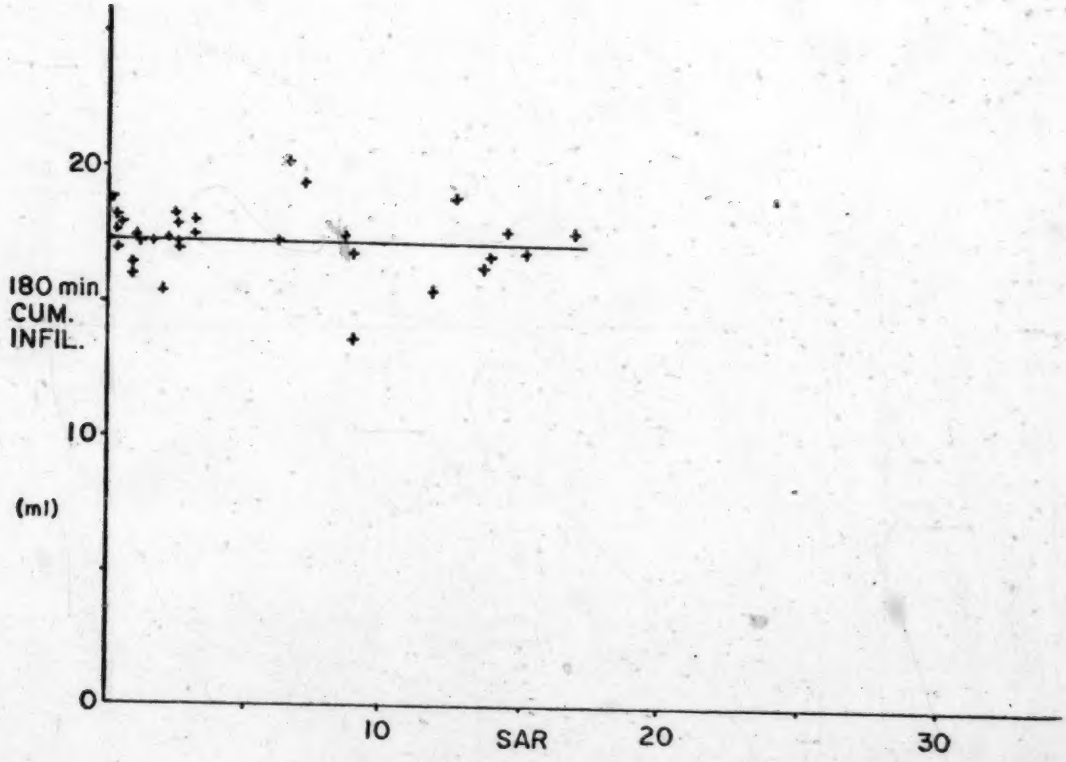

Figure 13. 180 min cumulative infiltration as a function of SAR for the A horizon of a Duagh-Malmo soils complex

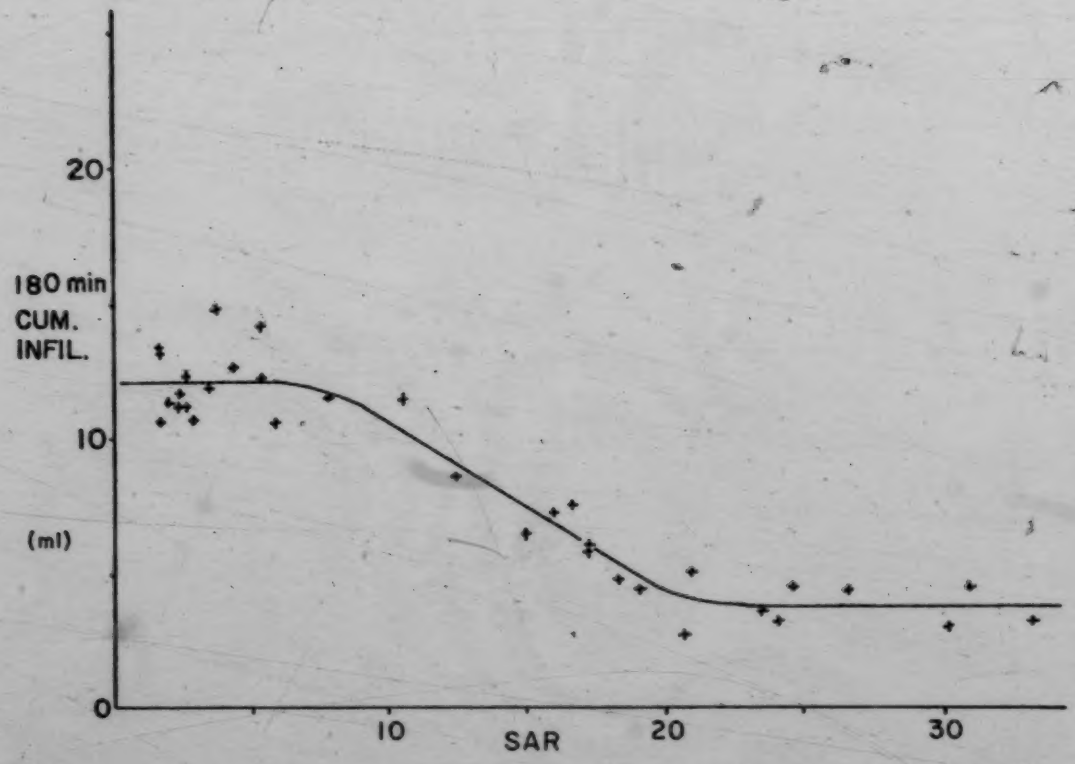

Figure 14. 180 min cumulative infiltration as a function of SAR for the B horizon of a Duagh-Malmo soils complex

cumulative infiltration is significantly correlated to the SAR (r^2 = 0.874). This shows that the adsorbed sodium level has a significant effect on the movement of water into unsaturated soil over this range. Above and below this range of SAR values, there is little control of water uptake by the SAR.

The cumulative infiltration measurements in the A horizon show no change with increasing SAR values. In Figure 13, the decline curve as found in the B horizon is not evident. Because of the differences in the exchange constant for the A and B horizons, the maximum ESP (9.6) of the A horizon is only slightly larger than the ESP (9.4) in the B horizon that causes reduction in cumulative infiltration. The SAR of 7 in the B horizon, corresponds to an SAR of 16.5 in the A horizon for the same ESP (9.4). The maximum SAR value in the A horizon is 16.9.

The infiltration data for all the observation times were fitted to the cumulative infiltration equation,

$$I = ct^a$$

where, I is the cumulative infiltration

t is the time of observation

c and a are empirical constants.

Since cumulative infiltration is the time integral of the infiltration rate (Hillel 1971), the infiltration equation is an extension of the Kostiakov equation (Kostiakov 1932),

$$i = act^{a-1}$$

where, i is the infiltration rate

t is the time of observation

c and a are empirical constants.

The Kostiakov equation fits well for short time infiltration (Swartzendruber and Huberty 1958) and for fine textured soils where the gradient due to matric potential remains high during infiltration (Taylor and Ashcroft 1972). The infiltration equations have been criticized for implying that the ultimate final infiltration rate approaches zero (Horton 1940), but due to the very short time of the experiment, it is unlikely that a steady rate of infiltration occurs. Infiltration vertically upward would result in zero flow when the gradient due to matric potential approaches the opposing gravitational gradient.

The cumulative infiltration data for the B horizon fit well to the infiltration equation, especially at the higher SAR, where the correlations are almost perfect ($r^2 > 0.96$). For the lower SAR, especially less than 5.0, the correlations are lower, although still very highly significant. The complete analysis for the fitting of the cumulative infiltration data and determining the constants a and c is presented in Appendix 7.4.4. The product of the constants a and c equals the constant ac in the Kostiakov equation which can be used to express the instantaneous infiltration rate at unit time (Swartzendruber and Huberty 1958). To determine the effect of the level of adsorbed sodium on infiltration rate, the constant ac was plotted as

the initial infiltration rate against the SAR (Figure 15) for the B horizon samples. The data from Figure 15 show similar results as that exhibited for cumulative infiltration (Figure 14). The upper plateau varies widely about a mean of 0.84 mL/min until the SAR reaches 7. The initial infiltration rate declines gradually until the SAR equals 21 where the uptake rate levels off to an average value of 0.25 mL/min. Between the SAR values of 7 and 21, the initial infiltration rate declines almost linearly (r^2 = 0.848) with respect to the adsorbed sodium. The effect of sodium on the initial infiltration rate is the same as its effect on the cumulative infiltration for the B horizon samples.

Since there was no significant decline in cumulative infiltration for the A horizon, the initial infiltration rates and cumulative infiltration equations were not determined for the samples in that soil layer. It was felt that no new information would be available from such an analysis.

4.5 Effect of sodium on water movement

For the disturbed B horizon samples from the Duagh-Malmo soil complex, the saturated HC and water infiltration into dry soil produces similarly shaped curves which correspond to the typical water movement decline curve (Figure 1). The sigmoid curve is also found in previous studies (van Schaik 1967; Felhendler et al. 1974; and Russo and Bresler 1977b).

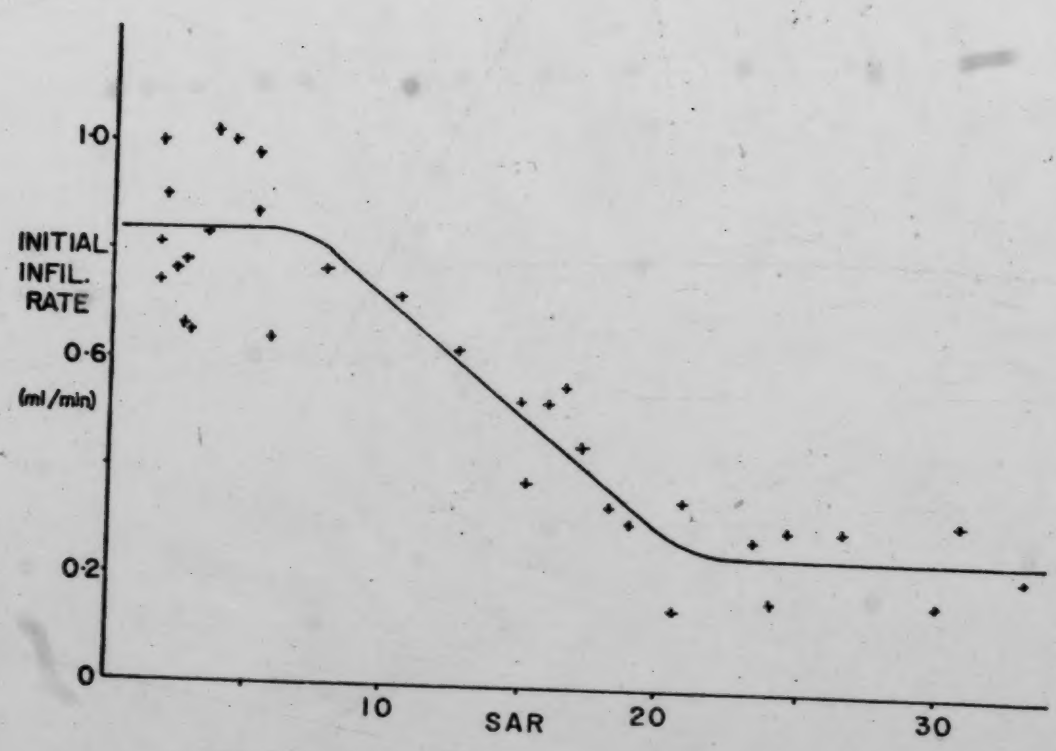

Figure 15. Initial infiltration rate as a function of SAR for the B horizon of a Duagh-Malmo soils complex

The curves for HC (Figure 12), 180 min cumulative infiltration (Figure 14) and initial infiltration rate (Figure 15) show upper and lower plateaux with respect to water movement versus SAR. In these areas that correspond to low and high levels of sodium respectively, there is no change in measured moisture movement with change in SAR. Between the two plateaux, exists a sloping region where the water movement parameter i.e. HC, cumulative infiltration or initial infiltration rate, is highly correlated to the SAR. Table 6 presents the critical SAR values that define the range of SAR where water movement is dependent on the sodium level in the soil.

The regions of the water movement decline curve reflect changes in soil hydraulic properties as they are affected by the processes of swelling, aggregate failure and deflocculation. In the upper plateau any swelling due to adsorbed sodium is not sufficient to reduce water flow in the soil. Although the sodium level is steadily increasing, neither the HC nor the infiltration is affected until a critical value is reached. The critical values of SAR are 3 for HC and 7 for infiltration in the B horizon samples (Table 6).

Rowell et al. (1969) stated that HC decreases begin when significant swelling occurs to control the HC. The swelling then causes HC decreases until deflocculation of the soil particles occur. The control of HC by swelling describes the sloping region quite well. Since the swelling

TABLE 6

CRITICAL SODIUM LEVELS FOR WATER MOVEMENT DECLINE IN THE B HORIZON OF A DUAGH-MALMO SOILS COMPLEX

Measurement	Lower Critical Level[1]		Upper Critical Level[2]		$(r^2)^3$
	SAR	ESP	SAR	ESP	
Hydraulic conductivity	3	3	14	18	.902
180 min cumulative infiltration	7	9	21	26	.874
Initial infiltration rate	7	9	21	26	.832

[1] Water movement begins to decline

[2] Water movement reaches a minimum value

[3] Coefficient of determination for correlation with SAR in the sloping region between the critical levels.

of the soil controls HC and swelling is controlled by the exchangeable sodium status, it follows that the ESP controls HC in the range that the adsorbed sodium controls swelling. As it has been shown that the SAR can be used to represent ESP, the SAR is closely correlated to the HC over the same range of adsorbed sodium. In the moisture movement studies for the B horizon, the SAR is significantly correlated with each water movement parameter ($r^2 > 0.85$) for the SAR range of 3 to 14 for HC and 7 to 21 for the infiltration measurements (Table 6). The correlation is negative indicating a decrease in water movement with increasing SAR.

The lower end of the sloping region indicates where aggregate failure and dispersion of the soil particles severely limits water movement. At the high levels of SAR, irreversible particle rearrangement causes the flow properties of the soil to be so restrictive that increasing the sodium level has negligible effect on moisture movement. In the B horizon, water movement is at a minimum when the SAR exceeds 14 for HC and 21 for infiltration.

Although the curves for water movement decline in the B horizon are similar, the critical regions over which sodium exerts its control on the soil hydraulic properties are different for the two methods of measurement. The magnitude of the change in the water movement parameter is also significantly different for the two studies. The saturated hydraulic conductivity decreases through four orders of magnitude between SAR 3 and 14 (Figure 12). Both

of the infiltration parameters only decrease to 30% of the initial value over a range of SAR from 7 to 21 (Figures 14 and 15). Infiltration into the dry sample is not as sensitive to the adsorbed sodium level as is the saturated water flow. The difference in sensitivity is noticeable in the magnitude to which the water movement parameter changes with increasing SAR values.

The initial moisture content has a profound effect on the change in water movement with increasing SAR values. Russo and Bresler (1977b) noted that the effect of high sodium levels on HC decreased as the moisture content was reduced although the shape of the curve remained the same (Figure 3). Likewise, Gardner et al. (1959) showed that reduction in water diffusivity into a sample is greatest under conditions of near saturation, although sodium affects the hydraulic properties of a soil at all moisture contents.

The small decreases in water movement at low moisture contents can be attributed to reduced clay swelling. The small layer of water around the particles restricts the development of swelling forces between the clay particles resulting in a reduction of the stresses on the aggregates and a reduction in particle rearrangement such as pore blocking by clay dispersion (Russo and Bresler 1977b). As the moisture content is reduced, the level of sodium that is necessary to restrict water movement increases.

A comparison of the data for the infiltration and HC in the B horizon shows the effect of moisture content quite

well (Table 6). Infiltration into a dry sample is not affected until twice the SAR that is necessary to cause reduction of saturated flow. Likewise, a higher SAR is tolerated in the dry sample than in the saturated samples before dispersion severely affects the moisture movement.

Not all the difference in water movement between infiltration and HC can be attributed to moisture content. The time of contact with the water is very important. The disturbed HC samples were allowed to reach saturation which took several days in the high SAR soils. The infiltration samples had, at a maximum, 180 min to allow swelling to proceed. Since Christenson and Ferguson (1966) noted that swelling is time dependent, the contact time between the soil and water could have a considerable effect on the amount of swelling in a sample.

Within the B horizon, flow into unsaturated soil is less affected by sodium adsorption than is flow in saturated soils. Not only is the SAR at which water movement is affected higher for the unsaturated soil than the saturated soil, but the magnitude of the decrease in moisture movement is smaller.

Water movement in the A horizon is not affected by the level of sodium up to an SAR of 17 as shown by no decline in either HC (Figure 11) or 180 min cumulative infiltration (Figure 13) with increasing SAR. Soil properties of the A horizon that are different from those of the B horizon result in such observations. The most important properties to

consider are the SAR-ESP relationship and the contents of organic matter and clay.

As shown earlier, the exchange constant for sodium is three times larger in the B horizon than in the A horizon. The difference in sodium adsorption does not allow the ESP to increase in the A horizon as rapidly with increasing SAR as it does in the B horizon (Figure 9). Although the range of SAR for the A horizon is approximately one half of that of the B horizon, the range in ESP is less than one third.

The difference in the exchange constants for the two horizons cannot completely account for the differences in sensitivity of water movement to SAR in the A and B horizons. HC begins to decrease in the B horizon at an ESP of 3 (Table 6). An ESP of 3 is achieved in the A horizon at an SAR of 5. If the responses to the adsorbed sodium level were the same for both horizons, the HC of the A horizon samples would decrease when the SAR exceeded 5.

The infiltration into the B horizon begins to decrease at an ESP of 9 (Table 6). Since the ESP of the A horizon does not exceed 10, it is not possible to determine whether the infiltration into the A horizon is affected by sodium levels that cause reduction of infiltration into the B horizon samples.

Besides altering the SAR-ESP relationship in soils, both clay and organic matter have an effect on the sensitivity of water movement to increasing SAR values. The organic matter acts as a bonding agent and can prevent the swelling

and deflocculation of aggregates under conditions conducive to clay swelling which would lead to HC decline (Collis-George and Smiles 1963). High clay contents reduce HC (McNeal et al. 1968) and increase the sensitivity to high sodium levels (Frenkel et al. 1978). The A horizon has one half of the clay content and three times the organic matter content of the B horizon (Table 3). Both of these differences would tend to cause the A horizon samples to be less sensitive to the effects of adsorbed sodium than the B horizon samples. The HC of the A horizon does not respond to the same ESP that causes HC decline in the B horizon. Up to an SAR of 17 and an ESP of 10, neither HC nor infiltration is affected by the level of sodium in the A horizon.

The USDA Salinity Laboratory classifies a soil as sodic if the ESP exceeds 15 (Richards 1954). This value is too high to recognize the hazards of sodium in a Duagh-Malmo soils association. The deleterious effects of sodium on the hydraulic properties of the B horizon are evident when the ESP exceeds 3. Once the ESP reaches 18, the sodium has sufficiently altered the soil hydraulic properties such that water movement is extremely slow. Above an ESP of 18, increasing the sodium has no effect on water movement. Once the ESP in the B horizon has exceeded 15, most of the damage to the soil structure has occurred.

Other soils from the lower horizons are affected by an ESP of less than 15. Glacial tills of SCL texture (van Schaik 1967) begin to show decreases in HC at an ESP of 5

and most of the reduction in HC occurs before an ESP of 15 is achieved (Figure 2).

The limit of an ESP of 15 for sodic soils does not allow the inclusion of certain soils that are affected by adsorbed sodium to the sodic soil category. The value of 15 is too high to be applied to fine textured soils of low organic matter content such as the B horizon of the Duagh-Malmo soils complex.

The Canadian system for soil classification uses an ExCa:Na ratio of 10 in the B horizon as the dividing point between Solonetzic and Chernozemic soils (Canada Soil Survey Committee 1978). As discussed earlier, the SAR value of 3 corresponds to this ratio of 10 for ExCa:Na in the B horizon (Figure 10). It is significant that the point where HC begins to decline is where the SAR is equal to 3 (Figure 12).

For the Duagh-Malmo soils complex, an ExCa:Na ratio of 10 is important with respect to water movement in the B horizon. The soils that have an ExCa:Na ratio of less than 10 (SAR > 3) exhibit the deleterious effect of adsorbed sodium on HC and are classified as belonging to the Solonetzic Order. The soils in this category are the Duagh and Wetaskiwin series. The Malmo soil occurs where the ExCa:Na ratio is greater than 10 (SAR < 3) and the level of adsorbed sodium has no effect on the HC of the soil. The criterium that the ExCa:Na ratio in the B horizon be less than 10 to classify a soil to the Solonetzic Order is suitable for the Duagh-Malmo soils association considering the effect of adsorbed sodium

on saturated water flow in that soil horizon.

5. CONCLUSIONS

A study was conducted into the effect of adsorbed sodium on the movement of water in the A and B horizons of a soils complex that included a Black Solonetz, a Black Solodized Solonetz and an Eluviated Black Chernozem. This soil association, referred to as the Duagh-Malmo soils complex, is developed on silty lacustrine materials. The experiment allowed a range in sodium levels within both soil horizons studied. The following conclusions from the study involve the interaction of some of the chemical and physical properties of the soil.

The Sodium Adsorption Ratio (SAR) can be used to adequately express the Exchangeable Sodium Percentage (ESP). Equations relating the ESP to SAR have been developed based on a Gapon type equation for both the A and B horizons of the Duagh-Malmo soils complex. For the A horizon,

$$ESP = \frac{(0.0076 + 0.0058\ SAR)\ 100}{1 + (0.0076 + 0.0058\ SAR)}$$

and for the B horizon,

$$ESP = \frac{(-.0180 + 0.0173\ SAR)\ 100}{1 + (-.0180 + 0.0173\ SAR)}.$$

Although the equations attribute over 90% of the variation in the ESP to variation in the SAR values, the relationships between the two parameters are quite different. An analysis based on the exchange constants for the Gapon type equation show that sodium is adsorbed three times more strongly in the B horizon than in the A horizon.

The difference in the adsorption of sodium between the two horizons is due to differences in soil properties, especially those affecting the nature of the exchange complex. A high organic matter content tends to decrease the adsorption of sodium and a large amount of clay increases the exchange constant for sodium. Because of the dependence of the adsorption of sodium on other soil properties, the relationship between ESP and SAR should be determined for a soil when comparing soils of different exchange properties.

The equation relating ESP and SAR developed by the USDA Salinity Laboratory (Richards 1954) does not adequately relate the solution and exchangeable cations in the Duagh-Malmo soils complex. This is particularly true for the A horizon of these soils. The equations developed in this study should be used when relating the SAR to the ESP in these soils.

In the Duagh-Malmo soil association, an SAR of 3 in the B horizon corresponds well to the exchangeable calcium-sodium ratio (ExCa:Na) of 10 that is the dividing point between Solonetzic and Chernozemic soils according to the Canadian system of soil classification. The relationship between SAR and ExCa:Na had the same high level of significance as the ESP-SAR relationship. In the Duagh-Malmo soil complex, the SAR value of 3 can be used to separate Solonetzic and Chernozemic B horizons.

Decline in water movement in the B horizon of the Duagh-Malmo soil complex tends to follow a sigmoid curve

composed of three segments. At low levels of SAR, there is little change in water movement with increasing SAR. At a critical SAR value, the water movement begins to decrease and its rate of decline is closely correlated to the increase in SAR. At higher sodium values, the rate of water movement levels off and is no longer affected by increasing SAR. This type of curve is produced by samples in the B horizon for measurements of both hydraulic conductivity and infiltration.

The saturated hydraulic conductivity is more susceptible to increased sodium levels and exhibits more dramatic decreases than vertical upward infiltration into an air-dry sample. In the B horizon of the Duagh-Malmo soils complex, the hydraulic conductivity decreased almost 100% in the range of SAR from 3 to 14. The two infiltration parameters, 180 min cumulative infiltration and initial infiltration rate showed decreases of 70% over an SAR range of 7 to 21. Soils of low moisture content are not as susceptible as saturated soils to the effects of increases in sodium levels, both in the SAR that causes reduction in water movement and the magnitude of the reduction.

Hydraulic conductivity decreases due to sodium adsorption are evident at an ESP as low as 3 for the B horizon of the Duagh-Malmo soils complex. Water flow is minimal when the ESP exceeds 18. Saturated water flow in this horizon can be severely limited by the effects of adsorbed sodium before the soil is classified as sodic (ESP > 15).

The saturated hydraulic conductivity begins to decrease at the same sodium level (SAR = 3) that corresponds to the boundary for chemical properties that divides Chernozemic and Solonetzic soils. All of the soils that are affected by adsorbed sodium (SAR > 3) in the Duagh-Malmo soils complex are classified as Solonetzic soils. Soils that show no effect of adsorbed sodium on saturated HC fall into the Chernozemic Order.

For the range of SAR values found in the field sampling, the adsorbed sodium level has no effect on water movement in the A horizon of the Duagh-Malmo soils complex. The A horizon is not as susceptible to the effects of adsorbed sodium as the B horizon because of different soil properties. The most important properties that contribute to the tolerance of SAR are a low rate of sodium adsorption, low clay content and high organic matter content.

The variability in the sodium levels of a Solonetzic soils complex is very high. It is difficult to prove that a given treatment has significantly affected soil chemical properties. The soils in this study had been treated for several years with various chemical amendments intended to alter the sodium levels in the soil. None of the ten chemical amendments showed any change in the SAR levels of the B horizon. Two of the nitrogen treatments (NH_4NO_3 and NH_4Cl) at 89 kg/ha of nitrogen reduced the SAR in the A horizon to below the level of the check plot. None of the other treatments affected the SAR levels in the A horizon.

Although the variability of the sodium levels are high in Solonetzic soil associations, other parameters such as the ESP-SAR relationship are stable within a soil horizon of the complex. It is possible to determine the sodium values that are harmful and critical for water movement. In amelioration of the soils, certain critical values should not be exceeded in order to have satisfactory water movement in the soil. On the Duagh-Malmo soil association, it is necessary that the SAR be less than 14 to begin improvement of saturated flow in the B horizon. To achieve maximum HC in that horizon, the SAR values must be less than 3. Water movement in the B horizon at moisture contents at less than saturation can withstand slightly higher SAR values with less effect on the hydraulic properties of the soil.

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7. APPENDICES

7.1 Exchange equations

1. Eriksson Equation (Bolt 1955)

$$\frac{\Gamma_1}{\Gamma} = \frac{r}{\Gamma\sqrt{\beta}} \sinh^{-1} \frac{r\sqrt{\beta}}{r + 4V_c\sqrt{c_2}}$$

Γ - surface charge density of the exchange complex

Γ_1 - surface charge occupied by the monovalent cation

$r = \frac{c_1}{\sqrt{c_2}}$

c_1 - solution concentration of the monovalent cation

c_2 - solution concentration of the divalent cation

$\beta + V_c$ - constants

2. Gapon Equation

$$\frac{\text{A ads}}{\text{B ads}} = k \left(\frac{\text{A sol}}{\text{B sol}}\right)^{\frac{1}{z}}$$

A ads - amount of A^{z+} on exchange complex

B ads - amount of B^{z+} on exchange complex

A sol - solution concentration of A^{z+}

B sol - solution concentration of B^{z+}

z - valence of cation

k - exchange constant

7.2 Soil profile descriptions (Bowser et al. 1962)

1. Duagh Silt Loam, (Du.SiL):

The Duagh soils are Black Solonetz developed on stone free lacustrine parent material. They are moderately well to imperfectly drained. A very thin Ae horizon may occur. These soils are usually intermixed with Wetaskiwin soils--the latter being in the slightly better drained position. Spots of saline meadow may occur throughout the Duagh areas.

Ah	0 - 5"	Black to very dark grey (10YR 2/1 - 3/1) silty clay; loose granular. pH 5.3
Bnt1	5 - 11"	Very dark greyish brown (10YR 3/2) clay; very hard columnar to coarse blocky; stained columns may have tapered tops. pH 5.8
Bnt2	11 - 19"	Brown to dark greyish brown (10YR 5/3 - 4/2) clay; blocky; less staining and definition of structure than in Bnt1. pH 7.7
Csk	at 20"	Dark greyish brown (2.5Y 4/2) clay; massive to small blocky. pH 8.0
C	at 48"	Dark greyish brown (2.5Y 4/2) silty clay to clay; massive. pH 7.7

The topography is level to gently sloping: usually in basinlike areas. The native vegetation cover is mainly varieties of coarse grass.

2. Wetaskiwin Silt Loam, (Wkn.SiL):

The Wetaskiwin soils are Black Solodized Solonetz developed on stone free lacustrine parent material. They belong to the same catena as the Duagh and Malmo soils and usually occur, topographically, between these two.

The following is a generalized description of a Wetaskiwin silty clay:

Ah	0 - 6"	Very dark brown to black (10YR 2/2 - 2/1) silty clay; granular to weak prismatic. pH 5.7
Ae	6 - 8"	Grey to grey brown (10YR 5/1 - 5/2) silty clay loam; platy. pH 5.6
Bnt	8 - 16"	Dark greyish brown (10YR 4/2) clay; hard columnar to fine blocky; stained. pH 6.5
Bntj	16 - 24"	Brown to dark greyish brown (10YR 5/3 - 4/2) clay; massive to coarse blocky. pH 7.4
Csk	at 24"	Dark greyish brown (2.5Y 4/2) silty clay; massive. pH 8.1
C	at 48"	Dark greyish brown (2.5Y 4/2) silty clay; massive. pH 7.9

The topography is level to gently undulating; on a macro scale usually a basinlike area.

3. Malmo Silt Loam, (MoSiL):

The Malmo series is a fairly well to well drained Eluviated Black soil developed on slightly saline lacustrine material.

A generalized description of a Malmo silty clay loam follows:

Ah	0 - 12"	Very dark brown to black (10YR 2/2 - 2/1) silty clay loam; granular to weak prismatic. pH 6.3
Ae	12 - 14"	Dark greyish brown to greyish brown (10YR 4/2 - 5/2) silty clay loam; medium platy to coarse weak blocky; a somewhat thicker Ahe may be present instead of an Ae. pH 5.5
Bt	14 - 36"	Dark brown to brown (10YR 4/3) clay; weak columnar to subangular blocky; slight staining near the top of this horizon. The lower part of this horizon can often be separated as Bm. pH 5.4
Ck	at 40"	Dark greyish brown (2.5YR 4/2) clay; massive; lime is usually low. pH 7.3
C	at 48"	Dark greyish brown (2.5YR 4/2) clay; massive; may be varved; may contain some salt. pH 7.6

The underlying till is sometimes found within 36 inches of the surface although it more often is at depths of over five feet and a sand layer may separate the lacustrine clay from the till.

The topography is level to gently undulating. These soils are usually found in slightly basinlike areas, actually post glacial laking basins. Duagh and Wetaskiwin soils are often geographically associated with Malmo; the Malmo occupies the better drained positions. The subsoil contains varying amounts of salt and the exchangeable sodium averages 10 per cent.

1. SOLUBLE CATIONS[1] IN THE A AND B HORIZON SAMPLES

Treatment	Replicate	Horizon	Ca	Mg	Na	K	SAR[2]	pH[3]	E.C.[4] (S/m)
				(meq/L)					
Experiment 1									
Check	1	A	1.75	1.11	10.66	0.50	8.9	5.6	----
		B	5.29	8.14	62.20	0.20	24.0	6.7	0.92
	2	A	2.69	1.89	1.72	1.20	1.1	5.6	0.085
		B	0.71	0.46	2.57	.22	3.4	6.1	0.046
	3	A	3.47	1.89	0.38	1.16	0.2	5.3	0.080
		B	1.55	0.50	1.74	0.07	1.7	5.2	0.040
$Ca(NO_3)_2$	1	A	3.87	3.04	0.98	1.24	0.5	5.4	0.090
		B	0.5	0.31	1.67	0.36	2.6	5.6	0.036
	2	A	2.2	1.11	3.18	0.73	2.5	5.3	0.069
		B	2.25	1.40	24.58	0.31	18.2	5.7	0.358
	3	A	2.99	1.60	0.46	0.87	0.3	5.4	0.068
		B	0,72	0.30	1.20	0.08	1.7	5.1	0.023
KNO_3	1	A	1.9	1.28	0.96	2.81	0.9	6.1	0.10
		B	1.27	0.54	1.65	0.60	1.7	5.8	0.043
	2	A	1.37	0.69	0.35	4.23	0.3	6.1	0.095
		B	0.47	0.24	1.11	0.16	1.9	5.1	0.020
NH_4NO_3	1	A	1.55	0.95	2.65	0.82	2.4	5.1	0.056
		B	1.17	0.43	9.35	0.25	10.5	5.5	0.114
	2	A	1.07	0.44	0.30	0.68	0.3	5.1	0.036
		B	0.57	0.24	2.76	0.10	4.3	5.4	0.041
	3	A	1.85	1.36	1.13	0.88	0.9	5.2	0.041
		B	0.66	0.42	1.67	0.16	2.3	5.6	0.034
$Ba(NO_3)_2$	1	A	1.92	1.60	0.23	1.40	0.2	5.7	0.069
		B	0.68	0.39	2.13	0.77	2.9	5.9	0.045
	2	A	1.85	0.99	1.22	1.18	1.0	5.7	0.059
		B	0.51	0.30	1.65	0.26	2.6	5.4	0.029
	3	A	1.85	1.23	0.33	1.20	0.3	5.7	0.069
		B	0.70	0.34	3.78	0.05	5.2	5.5	0.065

1. SOLUBLE CATIONS (cont)

Treatment	Replicate	Horizon	Ca	Mg	Na	K	SAR[2]	pH[3]	E.C.[4] (S/m)
				(meq/L)					
Experiment II									
Check	1	A	0.67	0.53	9.13	0.11	11.8	5.8	0.10
		B	1.49	1.51	25.4	0.15	20.6	6.8	0.049
	2	A	1.32	1.19	3.46	0.77	3.1	5.4	0.049
		B	0.76	0.53	3.00	0.07	3.7	5.7	0.047
	3	A	0.72	0.55	6.81	0.09	8.6	6.0	0.095
		B	1.22	3.5	35.89	0.10	23.4	7.4	0.49
NH_4NO_3	1	A	0.73	0.42	1.89	0.09	2.5	5.7	0.039
		B	8.86	13.17	49.37	0.12	14.9	6.8	0.722
	2	A	0.29	0.20	1.11	0.09	2.2	5.6	0.022
		B	0.97	0.70	7.16	0.04	7.8	5.5	0.14
	3	A	0.22	0.14	1.30	0.05	3.1	5.7	0.030
		B	6.49	11.93	48.28	0.01	15.9	7.1	0.079
NH_4Cl	1	A	0.73	0.57	2.02	0.40	2.5	4.7	0.064
		B	1.77	5.97	41.10	0.10	20.9	7.2	0.60
	2	A	0.92	0.59	1.63	0.42	1.9	4.5	0.056
		B	7.32	7.45	36.54	0.09	16.5	6.7	0.72
	3	A	0.84	0.61	1.37	0.23	1.6	4.4	0.056
		B	1.89	4.36	30.23	0.09	17.1	7.4	0.52
NaCl	1	A	1.26	0.83	9.13	0.47	8.9	5.7	0.10
		B	0.97	1.42	13.70	0.05	12.5	6.7	0.27
	2	A	0.52	0.43	9.35	0.23	13.6	5.8	0.14
		B	1.4	0.6	19.0	0.10	19.0	7.4	0.47
	3	A	0.40	0.30	7.16	0.12	12.1	5.6	0.11
		B	1.45	3.74	49.59	0.27	30.8	7.6	0.60
Na_2SO_4	1	A	0.79	1.23	16.96	0.45	16.9	5.5	0.70
		B	1.48	5.85	50.86	0.23	26.6	7.1	0.58
	2	A	0.84	0.76	11.31	0.22	12.6	5.4	0.13
		B	1.34	4.07	40.45	0.17	24.6	6.8	0.50
	3	A	0.80	0.37	5.44	0.44	7.1	5.7	0.066
		B	2.62	1.69	3.35	0.16	2.3	5.4	0.082

1. SOLUBLE CATIONS (cont)

Treatment	Replicate	Horizon	Ca	Mg	Na	K	SAR[2]	pH[3]	E.C.[4] (S/m)
			(meq/L)						
NH_4NO_3 + NaCl	1	A	0.62	0.37	4.28	0.56	6.1	5.5	0.066
		B	8.73	18.11	7.4	0.39	2.0	6.6	0.82
	2	A	0.62	0.42	6.74	0.66	9.4	5.4	0.082
		B	1.45	1.89	19.57	0.19	15.1	6.8	0.24
	3	A	0.41	0.31	8.76	0.07	13.8	5.2	0.095
		B	1.78	5.47	63.07	0.10	33.1	7.5	0.68
NH_4NO_3 + Na_2SO_4	1	A	0.66	0.59	11.96	0.21	15.1	5.4	0.12
		B	1.19	1.19	5.65	0.10	5.2	5.8	0.10
	2	A	0.41	0.28	8.48	0.08	14.4	5.4	0.11
		B	1.55	5.02	54.37	0.20	30.0	7.3	0.61
	3	A	0.57	0.30	4.31	0.31	6.5	5.5	0.060
		B	1.71	1.73	7.61	0.08	5.8	5.4	0.13

[1] Soluble cations (Ca, Mg, Na, K) of the saturated paste extract

[2] Sodium Adsorption Ratio

[3] pH of 2.5:1 water to soil suspension

[4] Electrical conductivity of the saturated paste extract in Siemens/meter = 0.10 x mmho/cm

2. EXCHANGEABLE CATIONS[1] IN THE A AND B HORIZON SAMPLES

Treatment	Replicate	Horizon	Ca	Mg	Na	K	CEC[2]	ESR[3]	Ca:Na[4]
				(meq/100g)			(meq/100g)		
Experiment I									
Check	1	A	8.80	1.21	2.83	1.20	47.6	.063	
		B	4.78	6.02		0.56	32.0		
	2	A	10.32	4.28	0.42	2.09	45.0	.009	
		B	15.0	8.23	1.1	1.59	37.8	.030	9.4
	3	A	18.28	4.63	0.27	2.16	49.1	.006	
		B	16.10	5.35	0.61	0.44	36.8	.017	26.4
$Ca(NO_3)_2$	1	A	13.8	4.25	0.30	1.17	40.6	.007	
		B	13.77	6.93	0.94	2.60	35.0	.028	14.6
	2	A	13.46	3.08	0.67	1.23	39.4	.017	
		B	7.99	4.12	7.26	0.99	33.2	.280	1.10
	3	A	14.19	3.45	0.31	1.82	55.8	.006	
		B	14.35	4.90	0.54	0.63	33.8	.016	26.6
KNO_3	1	A	16.6	5.76	0.31	4.51	45.4	.007	
		B	15.74	5.77	0.66	2.4	34.3	.020	23.8
	2	A	10.76	3.66	0.18	2.21	42.1	.004	
		B	14.78	6.41	0.42	1.18	31.2	.014	34.5
NH_4NO_3	1	A	15.31	4.77	0.47	2.08	46.7	.010	
		B	10.31	4.14	3.6	1.23	34.7	.116	2.86
	2	A	13.47	3.27	0.26	1.91	57.1	.005	
		B	9.60	3.08	1.91	0.65	26.8	.025	5.0
	3	A	8.78	3.60	0.28	1.45	34.3	.008	
		B	13.27	6.40	0.89	1.30	32.0	.029	14.9
$Ba(NO_3)_2$	1	A	15.53	5.61	0.21	2.08	47.8	.004	
		B	10.87	5.63	0.77	2.60	34.4	.023	14.1
	2	A	15.74	3.90	0.27	1.73	45.8	.006	
		B	7.30	2.49	0.46	0.94	23.5	.020	15.9
	3	A	14.59	4.41	0.23	2.32	39.6	.006	
		B	15.1	4.67	2.64	0.51	31.8	.091	5.7

2. EXCHANGEABLE CATIONS (cont)

Treatment	Replicate	Horizon	Ca	Mg	Na	K	CEC[2]	ESR[3]	Ca:Na[4]
			(meq/100g)				(meq/100g)		
Experiment II									
Check	1	A	7.74	4.19	2.72	0.60	35.2	.084	
		B	5.01	10.80		0.60	35.4		
	2	A	8.37	4.07	0.12	1.28	31.3	.004	
		B	7.68	4.48	0.92	0.52	31.4	.030	8.3
	3	A	5.24	3.00	2.79	0.61	39.6	.076	
		B	4.35	8.39	25.11	0.59	29.4		
NH_4NO_3	1	A	8.94	3.61	0.75	0.59	31.4	.024	
		B	8.43	9.07	7.58	0.48	14.9	.303	1.1
	2	A	5.24	2.93	0.55	0.79	32.6	.017	
		B	8.14	5.76	3.60	0.25	34.4	.117	2.3
	3	A	4.58	2.85	1.59	0.49	33.6	.050	
		B	4.32	7.85	8.74	0.59	15.9	.369	0.49
NH_4Cl	1	A	3.54	2.04	0.68	1.01	32.1	.022	
		B	5.32	11.98		0.50	34.0		
	2	A	3.44	1.32	0.31	0.81	26.4	.012	
		B	4.73	8.48	7.5	0.47	31.9	.307	0.63
	3	A	4.23	1.61	0.38	0.77	33.2	.012	
		B	6.55	8.68	7.5	0.35	31.9	.307	0.87
NaCl	1	A	6.39	3.11	1.64	1.40	31.8	.054	
		B	6.29	5.97	4.87	0.29	28.2	.209	1.3
	2	A	5.11	3.00	2.96	0.88	29.3	.112	
		B	6.37	10.79		0.62	36.8		
	3	A	5.44	2.80	3.05	0.93	32.9	.102	
		B	5.87	9.35		0.70	41.2		
Na_2SO_4	1	A	4.49	4.11	3.67	0.89	38.3	.106	
		B	5.15	12.3		0.64	47.3		
	2	A	4.89	2.75	2.54	0.68	40.4	.067	
		B	5.08	8.08		0.55	37.0		
	3	A	10.21	2.97	1.62	1.08	39.7	.042	
		B	14.57	5.56	0.70	0.58	41.0	.074	20.8

2. EXCHANGEABLE CATIONS (cont)

Treatment	Replicate	Horizon	Ca	Mg	Na	K	CEC[2]	ESR[3]	Ca:Na[4]
			(meq/100g)				(meq/100g)		
NH_4NO_3 + NaCl	1	A	8.3	3.02	1.54	1.38	36.8	.044	
		B	5.73	11.30	0.73	0.60	38.0	.020	7.3
	2	A	7.25	2.6	1.71	1.35	37.4	.048	
		B	10.69	10.81	4.38	0.71	40.2	.122	2.4
	3	A	5.06	2.44	2.58	0.43	45.8	.060	
		B	5.25	9.56		0.28	34.8		
NH_4NO_3 + Na_2SO_4	1	A	5.44	3.35	2.66	0.77	35.0	.082	
		B	13.04	7.55	1.65	0.47	38.0	.045	7.9
	2	A	5.31	2.14	3.48	0.54	39.0	.098	
		B	4.73	9.64	10.23	0.53	32.1	.468	0.46
	3	A	9.33	3.03	1.61	0.98	38.5	.044	
		B	8.08	5.10	1.86	0.33	39.8	.047	4.3

[1] Exchangeable cations (Ca, Mg, Na, K) calculated from subtracting the soluble cations from the ammonium acetate extractable cations

[2] Cation exchange capacity determined by the sodium acetate method

[3] Exchangeable sodium ratio

[4] Ratio of exchangeable calcium to exchangeable sodium in the B horizon

3. PHYSICAL MEASUREMENTS IN THE A AND B HORIZON SAMPLES

Treatment	Replicate	Horizon	% Carbon[1]	% Clay[2]	% Sand	% Silt	H.C.[3] (cm/hr)	Bulk Density[4] (g/cm^3)	Cum. Infil.[5] mL	Ini. Infil.[6] mL/min
Experiment I										
Check	1	A	6.08	22	15	63			15.6	
		B	1.05	43	3	54	3.91×10^{-4}	1.37	3.2	.170
	2	A	5.71	22	9	69	3.36	.88	17.2	
		B	0.72	53	1	46	1.48×10^{1}	1.32	11.9	.832
	3	A	5.67	23	12	65			18.8	
		B	1.13	48	1	51	9.36	1.23	13.4	.806
$Ca(NO_3)_2$	1	A	5.95	18	12	70	3.36	.88	15.9	
		B	0.84	53	1	46	1.62×10^{1}	1.32	11.2	.665
	2	A	6.14	21	12	67	8.93	.92	15.0	
		B	1.14	45	4	51	7.70×10^{-4}	1.31	4.8	.335
	3	A	5.46	20	12	68	8.59	.88	17.6	
		B	1.21	50	2	48	1.02×10^{1}	1.32	10.6	.740
KNO_3	1	A	6.59	20	10	70	3.36	.84	16.4	
		B	0.93	50	0	50	2.77×10^{1}	1.28	13.3	.995
	2	A	5.72	20	11	69	1.65	.83	18.1	
		B	0.84	49	3	48	8.70	1.38	11.5	.895
NH_4NO_3	1	A	6.46	20	14	66	9.06	.82	18.2	
		B	1.45	43	3	54	9.11×10^{-3}	1.30	11.5	.717
	2	A	6.10	21	11	68	1.05×10^{1}	.80	18.3	
		B	1.28	36	8	56	1.79	1.32	12.7	1.02
	3	A	4.87	21	10	69	4.09	.85	16.0	
		B	0.93	51	2	47	1.72×10^{1}	1.34	11.7	.759
$Ba(NO_3)_2$	1	A	7.32	17	14	69	5.11	.84	18.2	
		B	1.16	43	3	54	4.46	1.38	10.6	.648
	2	A	6.32	20	13	67	4.03	.92	17.3	
		B	1.46	25	10	65	2.35×10^{-1}	1.38	12.3	.781
	3	A	5.87	20	10	70	2.94	.89	16.9	
		B	0.97	49	2	49	2.79	1.34	12.2	.871

3. PHYSICAL MEASUREMENTS (cont)

Treatment	Replicate	Horizon	% Carbon[1]	% Clay[2]	% Sand	% Silt	H.C.[3] (cm/hr)	Bulk Density[4] (g/cm^3)	Cum.Infil.[5] mL	Ini.Infil.[6] mL/min
Experiment II										
Check	1	A	4.28	21	19	60	$3.78x10^{-1}$	1.14	15.4	
		B	1.56	47	10	43	$9.91x10^{-4}$	1.39	2.7	.154
	2	A	4.11	22	16	62	$6.67x10^{-1}$	1.11	18.0	
		B	1.26	39	6	55	$3.00x10^{-1}$	1.43	14.8	1.15
	3	A	4.43	20	16	64	$5.47x10^{-1}$	1.06	17.4	
		B	1.35	47	2	49	$8.46x10^{-4}$	1.43	3.6	.277
NH_4NO_3	1	A	4.24	21	18	61	$2.55x10^{-4}$	1.08	17.2	
		B	1.38	45	3	52	$4.02x10^{-4}$	1.42	7.5	.527
	2	A	3.98	20	20	60	$6.86x10^{-1}$	1.14	17.3	
		B	0.71	46	4	50	$8.06x10^{-3}$	1.44	11.5	.774
	3	A	4.43	23	14	63	$8.02x10^{-1}$	1.09	17.5	
		B	1.48	38	12	50			7.2	.534
NH_4Cl	1	A	4.40	21	21	28			17.8	
		B	1.52	46	9	45	$1.32x10^{-3}$	1.41	5.0	.353
	2	A	4.20	18	23	59	$7.98x10^{-1}$	1.15	15.4	
		B	1.73	39	12	49	$1.50x10^{-3}$	1.39	7.6	.563
	3	A	5.09	20	20	60	2.45	1.02	17.2	
		B	1.71	38	13	49	$1.45x10^{-3}$	1.37	6.1	.430
NaCl	1	A	4.44	24	17	59	2.46	1.08	16.8	
		B	1.82	36	14	50	$2.15x10^{-3}$	1.42	8.6	.619
	2	A	4.53	21	21	58	$4.16x10^{-1}$	1.11	16.2	
		B	4.96	45	6	49	$1.35x10^{-3}$	1.38	4.4	.314
	3	A	4.59	21	21	58			15.6	
		B	1.45	43	8	49	$1.53x10^{-3}$	1.35	4.5	.317
Na_2SO_4	1	A	4.72	25	18	57			17.6	
		B	1.96	47	5	48	$1.28x10^{-3}$	1.35	4.4	.301
	2	A	4.49	21	16	63	$8.03x10^{-1}$	1.05	18.8	
		B	2.16	44	7	49	$1.11x10^{-3}$	1.39	4.5	.304
	3	A	5.04	24	15	61	$8.65x10^{-1}$	1.07	19.3	
		B	1.21	48	5	47	$1.63x10^{-1}$	1.36	11.2	.488

3. PHYSICAL MEASUREMENTS (cont)

Treatment	Replicate	Horizon	% Carbon[1]	% Clay[2]	% Sand	% Silt	H.C.[3] (cm/hr)	Bulk Density[4] (g/cm^3)	Cum.Infil.[5] mL	Ini.Infil.[6] mL/min
NH_4NO_3 + NaCl	1	A	4.39	23	16	51			17.2	
		B	1.36							
	2	A	4.28	21	19	60	$4.91x10^{-1}$	1.08	16.8	
		B	1.16	51	5	44	$1.72x10^{-3}$	1.38	15.8	.381
	3	A	5.25	21	16	63	$9.38x10^{-1}$	1.02	16.7	
		B	1.30	42	5	53	$1.16x10^{-3}$	1.43	3.3	.216
NH_4NO_3 + Na_2SO_4	1	A	4.10	25	15	60	1.36	1.08	16.9	
		B	2.03	44	6	50	$3.43x10^{-1}$	1.34	14.2	.982
	2	A	4.96	22	15	63	$5.92x10^{-1}$	1.10	17.6	
		B	1.40	43	5	52	$1.11x10^{-3}$	1.38	3.0	.173
	3	A	4.47	25	13	62	1.07	1.03	20.2	
		B	2.19	34	12	54			10.5	.642

[1] Percentage carbon determined by the Leco furnace method

[2] Percentage clay, sand and silt determined by the hydrometer method

[3] Disturbed hydraulic conductivity

[4] Density of disturbed hydraulic conductivity

[5] 180 minute cumulative infiltration

[6] Initial infiltration rate

7.4 Statistical Analyses

1. Paired t-test to compare the chemical and physical properties of the A and B horizon samples

Property	A[1]	B[2]	$\bar{x}d$[3]	Sd[4]	t[5]
carbon (%)	5.10	1.37	3.73	0.188	19.8
clay (%)	21	44	23	1.10	20.9
sand (%)	16	6	10	0.674	14.8
silt (%)	63	50	13	0.914	14.2
pH	5.5	6.3	0.8	0.162	4.9
CEC (meq/100g)	39.3	33.4	5.9	1.58	3.7
SAR	5.5	12.3	6.8	1.25	5.4
EC (S/m)	0.080	0.29	0.21	0.044	4.8

$t_{.001} = 3.59$

[1] Mean of 35 A horizon samples

[2] Mean of 35 B horizon samples

[3] Mean difference A - B

[4] Standard error of the mean difference

[5] For all t values > 3.59 there is significant difference between the means for the A and B horizons ($p \leq 0.001$).

2. Analysis of variance of the regression of ESR on SAR for the A and B horizon samples

Regression Equation

A horizon $ESR = 0.0076 + 0.0058\ SAR \quad r^2 = 0.902$

B horizon $ESR = -.0180 + 0.0173\ SAR \quad r^2 = 0.902$

Source	ESS[1]	DF	MS	F	$F_{.005}$
A horizon	0.0035	34	0.0001		
B horizon	0.0437	25	0.0017	17	2.5

There is a very highly significant difference between the two regression equations ($p \leq 0.005$).

[1] Error sums of squares, calculated by subtracting the sums of squares due to regression from the total sums of squares.

3. Analyses of variances of the effect of treatments on the level of sodium in the A and B horizon samples

a) Experiment I A Horizon log (SAR) +1

Treatment	Rep 1	Rep 2	Rep 3	Treatment
Check	1.949	1.041	0.301	3.291
$Ca(NO_3)_2$	0.699	1.398	0.477	2.574
KNO_3	0.954	0.477	0.237*	1.668
NH_4NO_3	1.380	0.477	0.954	2.811
$Ba(NO_3)_2$	0.301	1.000	0.477	1.778
Rep	5.283	4.393	2.446	12.122

* calculated for missing replicate

Source	SS	DF	MS	F	$F_{.05}$
Replicate	.842	2			
Treatment	.638	4	0.160	0.581	4.12
Error	1.921	7	0.274		
Total	3.401	13			

There is no significant differences between treatments ($p \leq 0.05$)

b) Experiment I B Horizon log (SAR)

Treatment	Rep 1	Rep 2	Rep 3	Treatment
Check	1.380	0.531	0.230	2.141
$Ca(NO_3)_2$	0.415	1.260	0.230	1.905
KNO_3	0.230	0.279	0.126*	0.635
NH_4NO_3	1.021	0.633	0.362	2.016
$Ba(NO_3)_2$	0.462	0.415	0.716	1.593
Rep	3.508	3.118	1.664	8.290

* calculated for missing replicate

Source	SS	DF	MS	F	$F_{.05}$
Replicate	0.378	2			
Treatment	0.491	4	0.123	0.706	4.12
Error	1.220	7	0.174		
Total	2.089	13			

There is no significant differences between treatments ($p \leq 0.05$)

c) Experiment II A Horizon log (SAR)

Treatment	Rep 1	Rep 2	Rep 3	Treatment
Check	1.072	0.491	0.934	2.497
NH_4NO_3	0.398	0.342	0.491	1.231
NH_4Cl	0.398	0.279	0.204	0.881
NaCl	0.949	1.133	1.083	3.165
Na_2SO_4	1.228	1.100	0.851	3.179
NaCl + NH_4NO_3	0.785	0.973	1.140	2.898
Na_2SO_4 + NH_4NO_3	1.179	1.158	0.813	3.150
Rep	6.009	5.476	0.813	3.150

Source	SS	DF	MS	F	$F_{.005}$
Replicate	0.02518	2			
Treatment	1.8934	6	0.3156	8.83	5.76
Error	0.4287	12	0.03573		
Total	2.3473	20			

A very high significant difference exists between treatments ($p \leq .005$)

d) Duncan's Multiple Range Test for Experiment II A horizon to compare the treatment means of log (SAR)

Treatment	log (SAR)[1]	m[2]	LSR[3]	log (SAR)-LSR	[4]
NH_4Cl	0.294				a
NH_4NO_3	0.410	2	0.336	0.074	a
Check	0.833	3	0.352	0.481	b
NaCl + NH_4NO_3	0.966	4	0.363	0.603	b
Na_2SO_4 + NH_4NO_3	1.050	5	0.367	0.683	b
NaCl	1.055	6	0.371	0.684	b
Na_2SO_4	1.060	7	0.373	0.687	b

[1] mean of 3 replicates

[2] number of means compared

[3] Least Significant Range ($p \leq 0.05$)

[4] All treatments followed by the same symbol are not significantly different at ($p \leq 0.05$)

e) Experiment II B Horizon log (SAR)

Treatment	Rep 1	Rep 2	Rep 3	Treatment
Check	1.292	0.568	1.369	3.229
NH_4NO_3	1.173	0.892	1.201	3.266
NH_4Cl	1.320	1.210	1.233	3.763
NaCl	1.097	1.143	1.489	3.729
Na_2SO_4	1.425	1.391	1.328	4.144
NaCl + NH_4NO_3	0.301	1.179	1.520	3.000
Na_2SO_4 + NH_4NO_3	0.716	1.477	0.763	2.956
Rep	7.324	7.86	8.903	24.087

Source	SS	DF	MS	F	$F_{.05}$
Replicate	0.184	2			
Treatment	0.395	6	0.0658	0.518	3.00
Error	1.524	12	0.1270		
Total	2.103	20			

There is no significant difference between treatments ($p \leq .05$)

4. Infiltration parameters for B horizon samples

Treatment	Replicate	c^1	a	ac^2	$(r^2)^3$
Experiment I					
Check	1	0.47	0.361	0.170	1.00
	2	6.15	0.135	0.832	0.94
	3	8.63	0.093	0.806	0.67
$Ca(NO_3)_2$	1	6.99	0.095	0.665	0.85
	2	1.53	0.219	0.335	1.00
	3	5.97	0.124	0.740	0.78
KNO_3	1	6.80	0.146	0.995	0.76
	2	4.99	0.179	0.895	0.82
NH_4NO_3	1	2.22	0.323	0.717	1.00
	2	5.00	0.205	1.02	0.85
	3	7.05	0.108	0.759	0.77
$Ba(NO_3)_2$	1	6.64	0.098	0.648	0.76
	2	7.65	0.102	0.781	0.71
	3	3.06	0.284	0.871	0.98
Experiment II					
Check	1	0.44	0.352	0.154	1.00
	2	4.25	0.271	1.15	0.91
	3	0.94	0.296	0.277	1.00
NH_4NO_3	1	2.02	0.261	0.527	0.97
	2	2.53	0.306	0.774	0.99
	3	3.03	0.176	0.534	0.97
NH_4Cl	1	1.62	0.218	0.353	1.00
	2	3.01	0.187	0.563	0.96
	3	2.04	0.211	0.430	1.00
NaCl	1	2.59	0.239	0.619	0.98
	2	1.53	0.206	0.314	1.00
	3	1.51	0.210	0.317	1.00
Na_2SO_4	1	1.19	0.253	0.301	1.00
	2	1.09	0.279	0.304	0.99
	3	8.25	0.059	0.534	0.90

Treatment	Replicate	c^1	a	ac^2	$(r^2)^3$
NaCl + NH_4NO_3	1	NO SAMPLE			
	2	1.28	0.298	0.381	0.99
	3	0.82	0.264	0.261	1.00
Na_2SO_4 + NH_4NO_3	1	7.53	0.130	0.982	0.87
	2	0.48	0.360	0.173	1.00
	3	6.43	0.100	0.642	0.80

[1] c and a are the empirical constants from the cumulative infiltration equation,

$$I = ct^a$$

where, I is cumulative infiltration and
t is time

[2] ac is the constant from the first derivative of the cumulative infiltration equation,

$$i = act^{a-1}$$

where, i is infiltration rate and
t is time

[3] Coefficient of determination for the regression of I on t to determine c and a